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FOUNDED 1871

INCORPORATED BY ROYAL CHARTER 1921

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(II)

RECENT DEVELOPMENTS IN LONG-DISTANCE TELEPHONY

By A. C. TIMMIS, B.Sc., Associate Member.

SUMMARY

The paper deals with some of the research and development work carried out by the Post Office during the last few years, in connection with the transmission of speech over long lines.

With the rapid growth of international telephony since the advent of the thermionic valve, many new problems have arisen, requiring to be solved in accordance with geographical and other conditions peculiar to this country.

A brief mention is made of aerial lines, but the greater part of the paper is devoted to transmission over long cables provided with repeaters.

The principal subjects dealt with are:—

Two-wire and four-wire repeaters.

The operation of two-wire circuits at an overall equivalent of zero.

Echo-suppressors and voice-operated stabilizers.

Systems of carrier-current telephony developed by the Post Office for use on aerial lines, land cables, and sea cables.

Recent investigations regarding such general problems of long-distance telephony as cross-talk and transient effects are described.

INTRODUCTION

Apart from radio communication, long-distance telephony is now principally concerned with land or sea cables and the associated repeaters by means of which the line attenuation is neutralized. A brief reference to aerial lines will be made, however, in order to show the trend of recent developments in somewhat better perspective.

The paper is therefore divided under three headings:—
(1) Aerial (or open-wire) lines. (2) Land cables (aerial or underground). (3) Sea cables.

(1) AERIAL LINES

(a) Present Practice

Practically all aerial trunks are now worked as ordinary loop circuits, without phantoms, and d.c. signalling is used in order to facilitate operation.

Carrier telephony is used to an increasing extent, not only as a means of obtaining more circuits without adding wires or phantoming but also because the carrier circuit can be adjusted and maintained so that its overall equivalent (measured attenuation between terminals) is practically zero; and it is almost unaffected by inductive disturbances, from power or telegraph lines, which lie within the audio-frequency range.

On very long aerial lines such as those in use on the Continent, 3-channel carrier systems are employed, but the conditions here make these systems generally uneconomic, and the aerial-line single-channel (mains-operated) system developed by the Post Office* is used almost exclusively. About a dozen carrier circuits of this type are now working, mostly in Scotland, and more are being installed in various parts of the country. It is found that variations of line attenuation with the weather are not serious at the low carrier frequencies used, and records taken on typical Post Office lines have shown that no special means of regulation (such as pilot wires) are required to maintain the overall equivalent reasonably constant. On some of the railway companies' lines single- and 3-channel carrier systems of other types are used, and there are a number of power-line carrier telephone installations. The latter generally employ frequencies above 70 kilocycles per sec.

Provided the line attenuation does not exceed 26 decibels at 8 000 cycles per sec., the carrier circuit can be adjusted to zero equivalent between the 2-wire ends, since it is, in effect, a 4-wire circuit. When it is not extended to subscribers' or other lines a 600-ohm resistance is connected across each end of the carrier circuit, so that if variations of valves or line attenuation chance to reduce the equivalent below zero the circuit will not be unstable. The impedance of subscribers' lines is, usually, not so greatly different from 600 ohms that the circuit becomes unstable, even if the equivalent is 2 or 3 decibels below zero. Moreover, in the condition when a subscriber's line is connected but his telephone is hung up, the carrier circuit may become unstable, but the howl which builds up, being of carrier frequency, will not cause any serious disturbance to ordinary circuits on the route. The 600-ohm stabilizing resistances are fitted on nearly all the repeatered lines in the country, and will be referred to in more detail in Section (2).

(b) Future Development

The number of long circuits on aerial lines will no doubt decrease during the next few years, for the main aerial lines of this country, once the backbone of the trunk system, have all been divided up and used for comparatively short and unimportant circuits. The poles remain, but the number of wires has been greatly reduced. The less spectacular but more reliable cable is now generally accepted for all long and important trunks, except in remote districts such as the Highlands of Scotland, where the small number of circuits makes cable uneconomical. The single-channel carrier system (above referred to) costs less than erecting wires (on existing poles) even for 30 miles or so. It is therefore generally economical to provide new circuits of 30 miles or more in length by means of this carrier system, quite

* R. J. HALSEY: " A Simplified Carrier Telephone System for Open Lines," *Post Office Electrical Engineers' Journal*, 1933, vol. 26, p. 90.

apart from the advantage of a lower overall transmission equivalent. The number of carrier circuits which can be worked on the same pole route depends chiefly on cross-talk, and this, in turn, depends on line maintenance. A second channel can easily be added to the aerial-line single-channel system, if found desirable, and it may

a limited extent for junctions and short trunks. We have therefore only to consider the working of underground cable circuits provided with repeaters. Fig. 1 is a map showing the underground cable system of the country. There are about 40 repeater stations, housing from 20 to 700 repeaters. In addition, there are 1 300
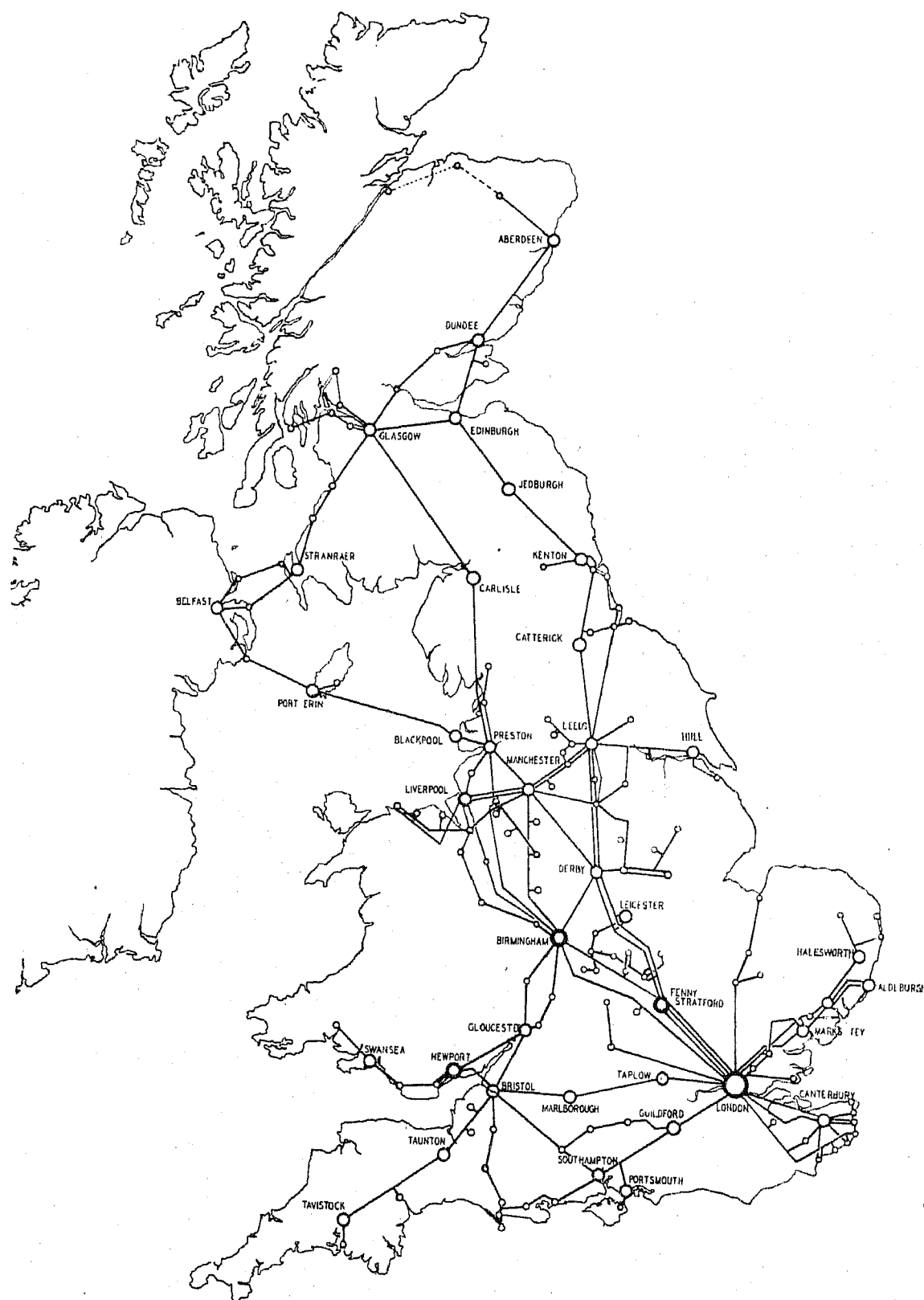
Fig. 1.—British trunk cable system and repeater stations, 1934.

safely be assumed that the number of circuits on an average line could be increased about 60 per cent by the use of carrier working. Such an increase would, however, usually be met by installing cable.

(2) LAND CABLES AND REPEATERS

(a) General

Conditions are unsuitable in this country for long aerial-cable routes, and aerial cables are only used to

toll repeaters on minor lines, and this number is rapidly increasing.

Repeaters are of two main types—2-wire and 4-wire.

(b) Two-wire Repeaters

The line attenuation permissible between 2-wire repeaters is now generally limited in practice by instability rather than cross-talk, and many attempts have been made by inventors to evade the fundamental

difficulty of equating line and balance over the working range of frequency. There are only two ways of doing this completely. First, we may use some form of voice-operated switch, which increases amplification in the direction of speech, while reducing it in the opposite direction. This device is known as a stabilizer or reaction suppressor. The second method, which depends on frequency-changing,* is not so convenient as the stabilizer, and would not lend itself to voice-frequency signalling systems with tuned receiving apparatus.

The most severe condition which any repeatered circuit has to meet is when both ends are disconnected. Until recently this occurred whenever the circuit was idle, but now all repeatered circuits, both 2-wire and 4-wire, in the Post Office system are automatically closed at the exchange ends by 600-ohm resistances when not in use. This means, in practice, that the margin of stability is least when two very short subscribers' lines are connected to the ends of the trunk circuit, a condition which gives about 5 decibels more stability than when both ends are disconnected. With the aid of this simple form of partial stabilization it has been possible to improve the overall equivalent of all 2-wire repeater circuits, so that its value now ranges from 3 to 7 decibels, according to the number of repeaters and uniformity of the cable. The introduction of the 600-ohm closing resistance was due to R. M. Chamney† and G. Manning.

(c) Four-wire Circuits

On any 4-wire circuit, if the line impedances are 600 ohms and the balances also 600 ohms, there will be a loss at each end of the singing path of 6 decibels (neglecting resistance in transformers) when the ends are open. The loss in the talking path is 6 decibels; thus the circuit will just be stable at an overall equivalent of zero.

In Fig. 2, first consider the transmission path AB, whose attenuation is measured in the usual way with a 600-ohm generator and 600-ohm closing impedance. Let the balance at each end be 600 ohms. At the sending end A, the extra loss due to a small resistance r in line and balance windings is given by

$$20 \log \left(1 + \frac{r}{2 \times 600}\right) = \frac{x}{2} \text{ decibels}$$

This is quite clear because the impedance of the fork transformer viewed from its 2-wire line terminals is 600 ohms, and we may regard the resistance r as between the generator G and a resistance of 600 ohms. Similarly, at the receiving end B, there is a loss $\frac{1}{2}x$ due to resistance r. Thus the total loss due to resistance is $\frac{1}{2}x + \frac{1}{2}x = x$ decibels, and this is made up by increasing the gain x decibels in each direction.

Now consider the stability of the circuit as usually measured, with 2-wire ends open. It is well known that the singing-path loss at each fork transformer is 6 decibels, neglecting transformer losses. When the resistance r is added the loss, calculated on the assumption that r is small, is $\frac{1}{2}x$. By symmetry the same loss occurs at the other fork; hence the singing-path loss is increased by x while the speech-path gain has been increased by x in each direction, and the stability is

worse by $2x - x = x$ owing to the addition of the resistances r. This corresponds to a change of $\frac{1}{2}x$ in the overall equivalent of the line.

It should be mentioned, incidentally, that the argument does not apply to a 2-wire repeater, where Z_L and Z_B are nearly equal. Using the ordinary formula $20 \log \left[(Z_L + Z_B)/(Z_L - Z_B)\right]$, we find that the increase in singing point is x, not $\frac{1}{2}x$ as in the 4-wire case. Thus the resistance does not affect the stability of intermediate repeaters in a 2-wire circuit, but if there are terminal repeaters the end conditions are the same as in a 4-wire circuit.

Evidently, then, an added resistance in the line and balance windings requires an increase of gain, while only increasing the singing point half as much. It is therefore advantageous, from the point of view of stability, to reduce this resistance by using thicker wire. Less space is then available for the other windings, but their consequent higher resistance has no effect on stability because the extra gain required to make up this resistance loss is precisely equal to the extra attenuation in the singing path.

With the older-type hybrid coils still in use on a majority of trunks the resistance of line and balance
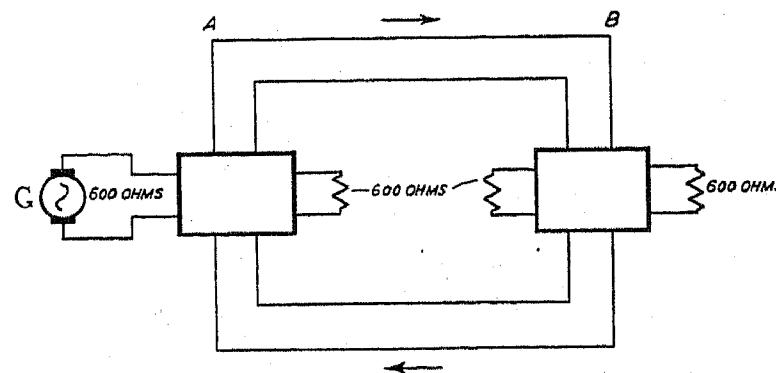

Fig. 2

windings is rather high, and there is appreciable leakage inductance, the result being that the minimum overall equivalent (the circuit being equalized up to 2 000 cycles per sec. at least) is 2·75 decibels. With the later-type hybrid coils the minimum equivalent is reduced to 0·35 decibel with equalization up to about 2 400 cycles per sec.—an improvement in stability of 2·4 decibels. The important point is, however, that experience in this country has shown that 4-wire trunks with the older-type coils can safely be worked at zero equivalent. This improvement of 2·4 decibels secured by the new-type coils could be taken advantage of by lowering maintenance standards, so that an increased " drift," or variation of overall equivalent, was tolerated; but the advantage is dubious and it is preferable to raise, rather than lower, the maintenance standards, so that 2-wire circuits of zero equivalent may be used as widely as possible. Under the best conditions a 2-wire circuit cannot be quite as stable as a 4-wire; but, as will be seen later in Section (2) (d), the difference can, with modern cables, be made less than 2·4 decibels, and the minimum stable equivalent (with ends open) kept below 2·75 decibels, which has been proved safe on zero-loss circuits during the past 2 or 3 years.

A 4-wire repeater consists simply of two amplifiers, one for the " go " and one for the " return " line. In

the standardized main-line type used by the Post Office, the maximum gain is 40 decibels when used as a " flat " amplifier. In practice, as the line attenuation always rises with frequency, the gain of the repeater is modified by means of the equalizer—a resonant circuit in series with the input-transformer primary—to correspond with the attenuation of the line preceding the repeater. In general, it is convenient to equalize up to 0·75 of the cut-off frequency of a loaded line.

Although long lines require several repeaters of this type housed in special buildings and subjected to regular tests, a simplified type of repeater has been introduced for minor trunk lines and occasional use in main lines.*

some advantage over the valve-and-relay type, in that its operation is gradual. There is practically no danger of simultaneous speech from both ends of the line causing a " lock out." Moreover, the effects of line noise are rather less troublesome than with the valve-and-relay type.

With the introduction of zero circuits and telex working, however, the valve type of suppressor has required modification to prevent occasional false operation due to slight maladjustments or change of valve characteristics, and to allow of the suppressor being placed near one end of the line.
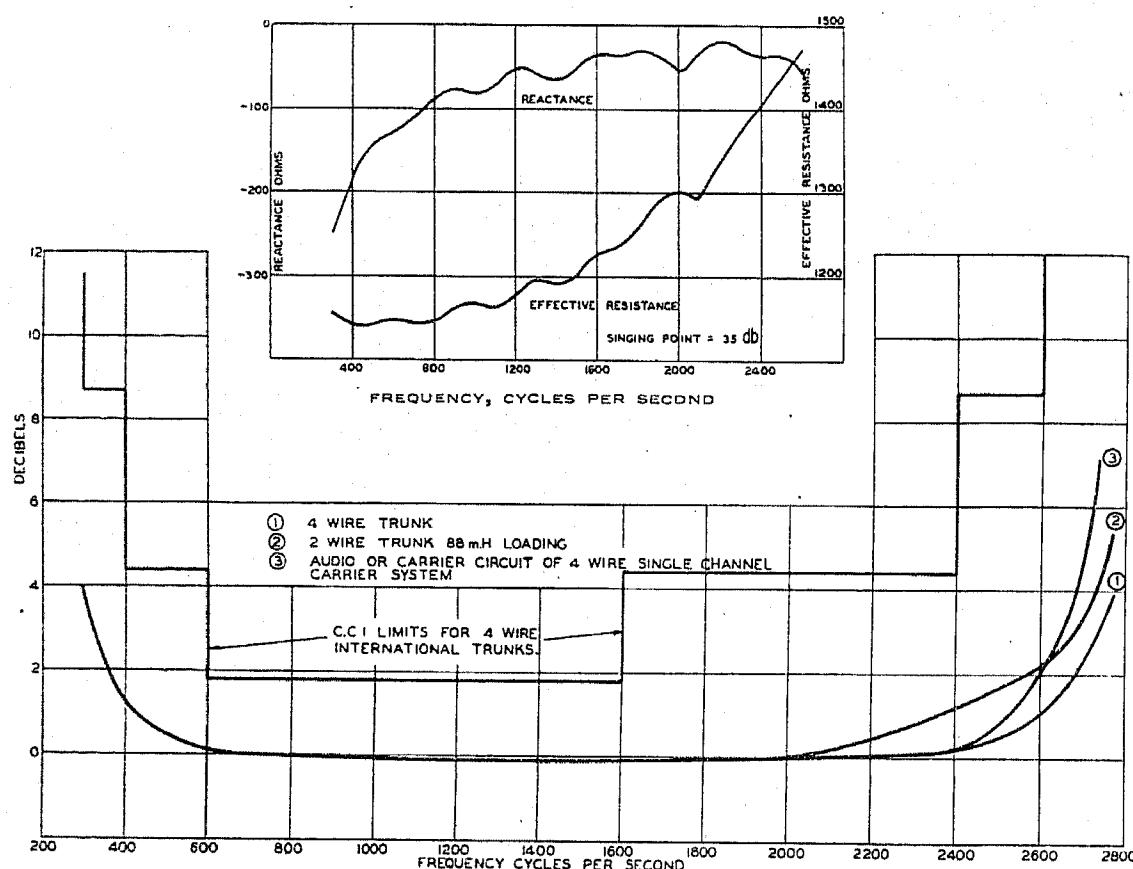
" Telex " is the name given to a system, recently

Fig. 3.—Typical repeater-section impedance curve for 25-lb. P.C.Q.T. cable, 88-mH loading at 1·136-mile spacing.

These " amplifying units " or " toll repeaters " are operated from the supply mains, with automatic change-over to batteries in case of mains failure, and the filaments are heated by unrectified alternating current. Toll repeaters can be installed in any telephone exchange where mains supply is available, and are practically unattended.

Equalizers are not required for the comparatively short lines concerned. These repeaters cost much less than main-line repeaters, and their use on the shorter lines of the trunk system effects a great economy of line plant together with a general transmission improvement.

(d) Electrical Echoes

Under modern conditions the echo effect on any long trunk adjusted to a satisfactory overall equivalent is such that echo-suppressors are necessary. The valve type of suppressor now generally used in Europe has

developed by the Post Office, in which teleprinter signals are transmitted over the public telephone system by means of a voice-frequency carrier. The converting apparatus is located at the subscriber's premises. Electrical echoes have to be suppressed, as in the case of speech, but the conditions as regards timing of suppressors are more severe. They have been met, however, by simple modifications. An improved type of echo-suppressor has recently been invented by Ryall* in which valves are replaced by copper rectifiers, and, instead of the repeater amplification being reduced by the application of negative grid voltage, variable attenuators consisting of series and shunt rectifiers are used in front of the repeaters. A diagram of the valve-less suppressor was given in a recent paper by B. S. Cohen.†

Speech current from the output of, say, the " go " repeater, rectified by a copper rectifier, makes the grid

* A. C. TIMMIS: " The Toll Repeater," *Post Office Electrical Engineers' Journal*, 1933, vol. 26, p. 29.

* British Patents Nos. 415767, 416372.
† *Journal I.E.E.*, 1934, vol. 75, p. 133.

of the return output valve slightly positive. The anode current of the valve is increased (it is, in effect, doing duty as a d.c. amplifier), and this alters the bias of the rectifiers forming the attenuator in front of the return repeater in such a way that its loss increases by 20 or 30 decibels, thereby suppressing the return repeater. The anode circuits of the two output valves are differentially connected, so that an interlocking effect is obtained between the two directions. This prevents false operation under any practical conditions. The tuned rejector circuits, in conjunction with the auxiliary rectifiers, were used to make the suppressor inoperative in the neighbourhood of two signalling frequencies, 600 and 750 cycles per sec., without impairing its sensitivity to speech.*

The advantages of the valveless suppressor are: (i) economy in first cost and maintenance; (ii) equally reliable operation (due to the differential locking principle) when placed at one end or in the middle of a line; (iii) tuned rejector circuits can be added conveniently to render the suppressor inoperative at the two frequencies used in one type of voice-frequency signalling system.

The valveless suppressor has the further advantage that it can be used in a 2-wire repeater. Hitherto suppressors have not been needed in 2-wire circuits, because any 2-wire line long enough to have an appreciable echo time would generally be unstable if adjusted to such an equivalent that the echo effect was serious. Cable manufacture has recently improved to such an extent, however, that, within certain limits, it is practicable for 2-wire circuits to be worked at zero equivalent.

Owing to the simplicity and stability of 4-wire circuits and the facility with which they can be connected together it has become the universal practice to provide long-distance trunks on a 4-wire basis. There would obviously be considerable economy of circuits if sufficient stability and transmission efficiency could be obtained with two wires, and an account of the progress which has been made towards this object may be of interest.

The London–Liverpool cable (25-lb. conductors, loaded with 120 mH at intervals of 2 000 yards) has a very smooth impedance/frequency curve. In this cable 2-wire circuits, 200 miles in length and containing four repeaters, are working with zero equivalent and a margin of stability under the worst possible terminal conditions —i.e. with a short subscriber's loop at each end—which is rather more than that of a 4-wire zero circuit with old-type hybrid coils. When two of these circuits are joined together at Liverpool, the resulting 400-mile trunk has a margin of 2 or 3 decibels under the worst terminal conditions.

Fig. 3 shows a typical repeater-section impedance curve for the Liverpool–Glasgow cable, with the overall frequency response of a 2-wire Liverpool–Glasgow trunk (200 miles).

This result has only been achieved by using hybrid coils of improved design,† accurate repeater balancing, and adjustment of the equalization at each repeater. In a 4-wire circuit it is not essential for the gain of each repeater to match the adjacent line, so that equalizing is a comparatively simple matter. When a 2-wire cir-

cuit is correctly set up, the unbalances at the ends, when the circuit is on the verge of instability, should be greater than at any intermediate repeater. Echo conditions are then similar to those on a 4-wire circuit, and an echo-suppressor must be fitted.

Any circuit which is adjusted to zero, when measured in the usual way with an input power of 1 mW, may become unstable through momentary disconnections at one or both ends, together with reduced hysteresis resistance of loading coils at very low current values; and an echo-suppressor serves to limit the singing current, which can only build up to a magnitude which is too small to disturb other lines through cross-talk. As soon as the singing current reaches a certain value it operates the suppressor, is cut off, builds up again, and so on.

It is important to distinguish between this useful limiting effect of an echo-suppressor and " stabilizing " or preventing any singing current from building up. The latter is the function of a " stabilizer " or " reaction suppressor," and will be dealt with in Section 2 (e).

Echo-suppressors are required to suppress both talker and listener echoes on long 2-wire circuits. The prin-
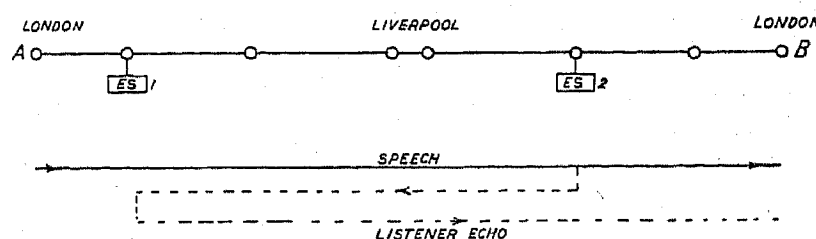

Fig. 4.—Experimental 2-wire circuit.

ciple will be readily understood by considering the experimental 400-mile circuit shown in Fig. 4. There are two suppressors, E_1 and E_2.

If E_1 is cut out, a talker at A finds a serious echo effect, due to the summation of echoes at the repeaters between A and E_2. Therefore E_1 is necessary to suppress talker echo. Similarly E_2 is necessary. When, however, speech from A operates both E_1 and E_2, echoes from the intervening repeaters may be reflected at E_1 and travel towards B, passing through E_2 with the speech from A, and being heard as additional sounds rather like transients. The effect is very slight, provided the distance between E_1 and E_2 is not too great. The best arrangement is obviously to place the suppressors near the one-quarter and three-quarter points, not at the ends.

(e) Stabilizers

The first voice-operated stabilizer to be put into service was installed at Taunton, in the 4-wire portion of the London–Channel Isles trunk.* The shunting loss, which is normally across the line in the idle condition, is small at low speech frequencies and rises to a maximum at 2 000 cycles per sec. Thus, for instance, the operating conditions are not so exacting as in the case of the transatlantic radio channel.

The operation of the impedance-valve type of stabilizer is limited by two factors. First, line noise may cause false operation if the device is made too sensitive; and,

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* These rejector circuits are not now required, the method of signalling having been altered so that simultaneous transmission in opposite directions does not occur.

† See Section 2 (b) above.

secondly, if it is not sensitive enough, initial syllables may be lost. This effect is known as " clipping." Both these troubles, hitherto regarded as inherent in any voice-operated stabilizer, have been almost completely overcome in the stabilizer invented by Ryall. It is to some extent a development of the valveless echo-suppressor, and is applied both to lines and to subscribers' microphone-loud-speaker arrangements.

The new stabilizer works equally well either in association with a 2-wire repeater or in a 4-wire line. The method of operation obviates the necessity of a time-delay, such as usually obtains on a 4-wire line.

It has an important application in the trunk service in order to enable 2-wire circuits which, owing to irregular line impedance, would normally have to be adjusted to an overall equivalent of several decibels at 800 cycles per sec. and much more at higher frequencies, to be worked at zero equivalent, and equalized up to, say, 2 000 cycles per sec. or more. There is good reason
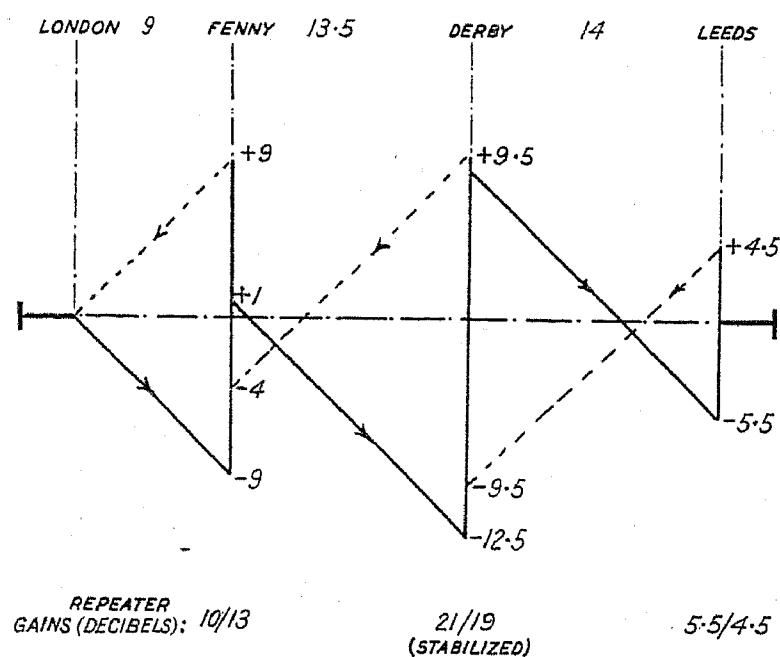
charges a shunted condenser which determines the hang-over time in the usual way. If the hang-over time is made long enough to avoid a jerky effect in the speech and to deal with an echo returning in, say, 200 milliseconds, speech or any noise in the go direction will keep the return direction suppressed and speech may be prevented from getting through. If the hang-over is temporarily reduced, however, by speech trying to get through, it will succeed, provided that a peak value greater than the noise occurs. There is, in the Ryall stabilizer, a break-in device which, by means of a rectifier shunting the resistance of the resistance-condenser combination controlling the hang-over time, reduces the latter to a very small value when speech arrives on the return side of the stabilizer and finds the way blocked by speech or noise on the go line. The arrangement is applied to both sides of the stabilizer, and the rectifier circuits N_1 and N_4 are interlocked in an ingenious way.*

It may be noticed that an output level of + 9 decibels

Fig. 5.—Typical 2-wire stabilized circuit.
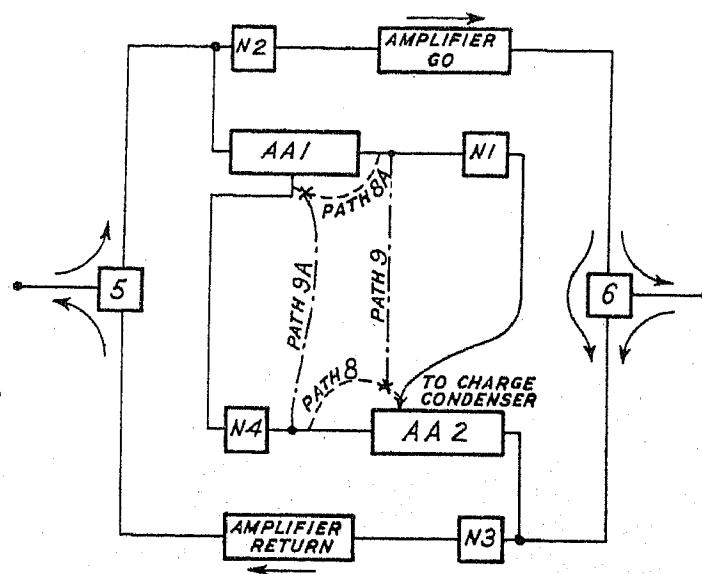
Fig. 6.—Schematic diagram of 2-wire voice-operated stabilized repeater.

to hope that it will be possible to fit these circuits into the general trunk switching plan, like zero 4-wire circuits, with obvious economy.

The method will be made clear by taking as an example a London–Leeds circuit, having repeaters at Fenny Stratford, Derby, and Leeds. The loading is 176 mH at 1·6-mile intervals, which results in a rather low cut-off frequency and an irregular impedance. A level diagram is shown in Fig. 5, from which it will be seen that the gain has been concentrated as much as possible at the (stabilized) Derby repeater, in order to reduce the gains of the other repeaters well below singing point. The principle of the stabilizer itself is illustrated in Fig. 6.

In front of the go and return amplifiers, variable attenuators (N_2 and N_3) similar to those used in the echo-suppressor are fitted. Speech in the go direction operates, through the auxiliary amplifier AA_1, suitable rectifier networks which (i) suppress the return direction by increasing the attenuation of N_3, and (ii) open up the go direction by reducing the attenuation of N_2. The speech current amplified by AA_1, and rectified,

is used at Derby. Although 4 or 5 decibels higher than usual, this does not involve appreciable risk of over-loading, for the usual level was fixed—by international agreement—so that exceptionally loud speech at the input of the trunk would produce no noticeable distortion. At the time when the agreement was made there was no particular reason to use the highest permissible level. Oscillographic records have been taken of the speech currents in both directions, using sound film instead of actual speech, and a cinematograph film has been made to illustrate how the peaks of speech currents can overcome line or room noise. [The film, with recorded commentary, was shown at the meeting.] Fig. 7 is a view of the board used in making the film. This principle of enabling a speaker to overcome line or room noise, so that there is no danger of his being kept out of circuit except when the other person is speaking, has been of the greatest value in connection with loud-speaker telephones and conference systems. These systems are outside the scope of the paper, but it may be mentioned that the prospect of an extensive

* British Patent Nos. 430158 and 430567.

use of high-quality microphones and loud-speakers is one important factor tending to a higher grade of transmission on both trunk and local lines.

(f) Phase Distortion, or Transient Effect

On very long lines a form of distortion occurs which is generally known as the "transient effect." The velocity of the high frequencies being less than that of the middle frequencies which are most prominent in ordinary telephone speech, the high-frequency components involved in the starting or stopping of a signal will arrive later than the steady-state frequency. The listener hears the transient as a sort of chirping sound at the end of a syllable, and these chirping sounds reduce the intelligibility to a slight extent and cause a certain amount of annoyance.

In order to determine the importance of the transient effects, for English speakers, a series of articulation tests was made, using a 1 300-mile line. This line was composed of London–Birmingham loops in the same cable
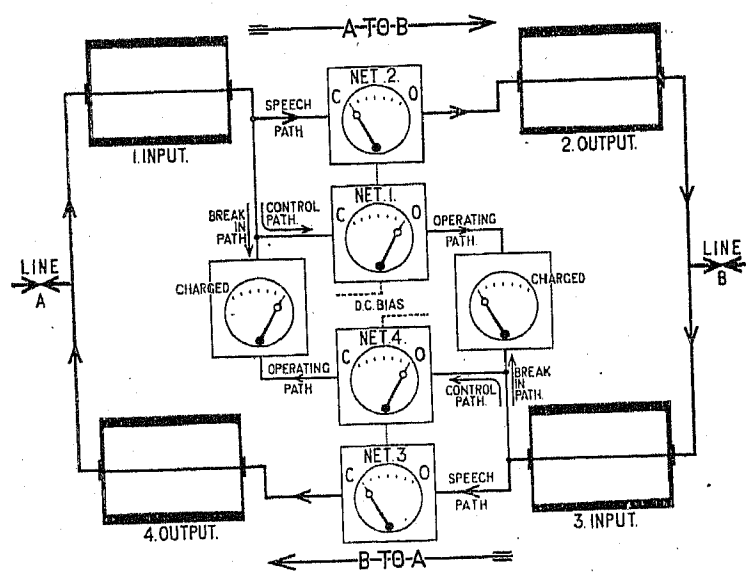

Fig. 7

NOTE.—In the windows 1, 2, 3, and 4, moving wave-trains represent speech currents, while the six needles indicate switching operations.

loaded with 120 mH at intervals of 2 000 yards. With the aid of repeaters the overall equivalent was made zero between 200 and 2 800 cycles per sec., and filters were used to reduce the amplitude of the highest transmitted frequency in some of the tests.

There were four types of impairment present:— (i) The transient effect; (ii) non-linear distortion; (iii) limitation of frequency band; (iv) noise.

To separate the transient effect from the other three factors comparative articulation tests were made, taking all the usual precautions to average out the inevitable variations, first with the complete circuit, and secondly with the repeaters connected through artificial lines and one London–Birmingham loop, with artificial noise equal to the actual noise on the 1 300-mile circuit. No definite difference in percentage articulation was found between the two cases, and it must be concluded that (for English, at any rate) this amount of transient effect does not appreciably impair articulation. It does, however, cause a certain amount of annoyance to the listener when the received volume is fairly high. The degree of annoyance can only be measured by a series of judgment tests. So far it would appear that the limit of 30 milliseconds

fixed by the C.C.I. for the difference between the times of transmission of the highest and lowest transmitted frequencies (which was exceeded in these tests) is not too high for commercial telephony.

It has sometimes been stated that the insertion of a filter to lower the cut-off to about 2 400 cycles per sec. reduces the magnitude of the transient effect. This statement was tested by several observers, and in no case was it considered that the transient was reduced by lowering the cut-off from 2 800 to 2 400 cycles per sec. Apparently there is so little energy in telephone speech between 2 400 and 2 800 cycles per sec. that the transients due to this frequency range are quite inaudible.

(g) Carrier-Current Working

For long trunk cables of the type now in general use, the most convenient system of carrier working is to superpose one 4-wire carrier channel on each audio-frequency circuit, both audio-frequency and carrier
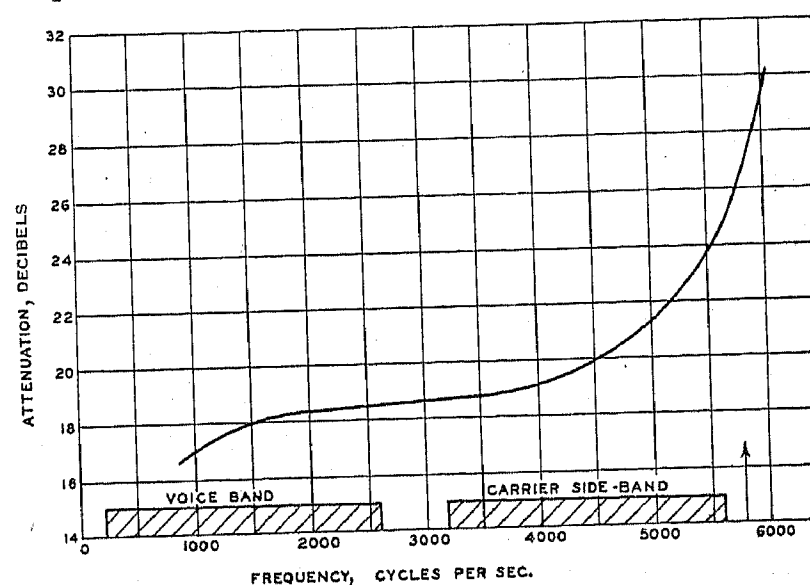

Fig. 8.—Attenuation of Carmarthen–Haverfordwest cable pair, and original frequency-ranges of P.O. cable carrier system. Cut-off = 6 600 cycles per sec.

currents being amplified by the same repeaters. Suitable loading must, of course, be used.

The same number of circuits can be obtained by means of the German *Zwei-band* system,* but this has several disadvantages, especially in the case of long circuits containing numerous repeaters. Filters are necessary at every repeater, and this means increased propagation time. Also, it is an essential feature of the system that simultaneous transmission in both directions should not take place. Therefore voice-frequency telegraphs cannot be used. For these and other reasons a single-channel 4-wire carrier system such as that developed by the British Post Office for loaded cables is preferable.

The heaviest loading which can be used (without departing from the standard spacing of 2 000 yards) is 30 mH, which gives, for a capacitance of 0·065 μF per mile, a cut-off frequency of 6 600 cycles per sec. With a carrier frequency of 5 800 cycles per sec. using lower side-band only, two circuits of very good quality can be obtained, both audio-frequency and carrier channels being flat between 300 and 2 500 cycles per sec. It

* A. C. TIMMIS: "Carrier Current Telephony," Institution of Post Office Electrical Engineers, Professional Paper No. 131, p. 31.

facilitates equalizing, however, to use a cut-off frequency of 7 800 cycles per sec., with the same carrier frequency. The corresponding loading-coil inductance is 22 mH. In Fig. 8 is shown the division of the available frequency range.

A subsequent modification is the use of a carrier frequency of 6 000 cycles per sec. The only changes required are suitable alterations to the filters. Existing carrier circuits have not been altered. As in the aerial-line carrier system, copper-oxide rectifiers are used for modulating and demodulating, and consequently only 2 valves are needed per channel end, apart from the 2-valve oscillator, which generates the carrier supply for 6 channels.

at a suitable level. This arrangement is shown in Fig. 13.

Unlike most carrier systems, in which the line attenuation must be made up by amplification in the terminal apparatus, the 4-wire cable carrier system depends on the line repeaters, and terminal amplification is therefore required mainly to ensure that the metal rectifiers work at suitable levels of speech power. The repeater output levels of audio and carrier frequencies are determined by the " cross-modulation," which arises almost entirely from the non-linearity of the repeater valves and makes itself felt as (unintelligible) cross-talk between the audio-frequency and carrier channels.
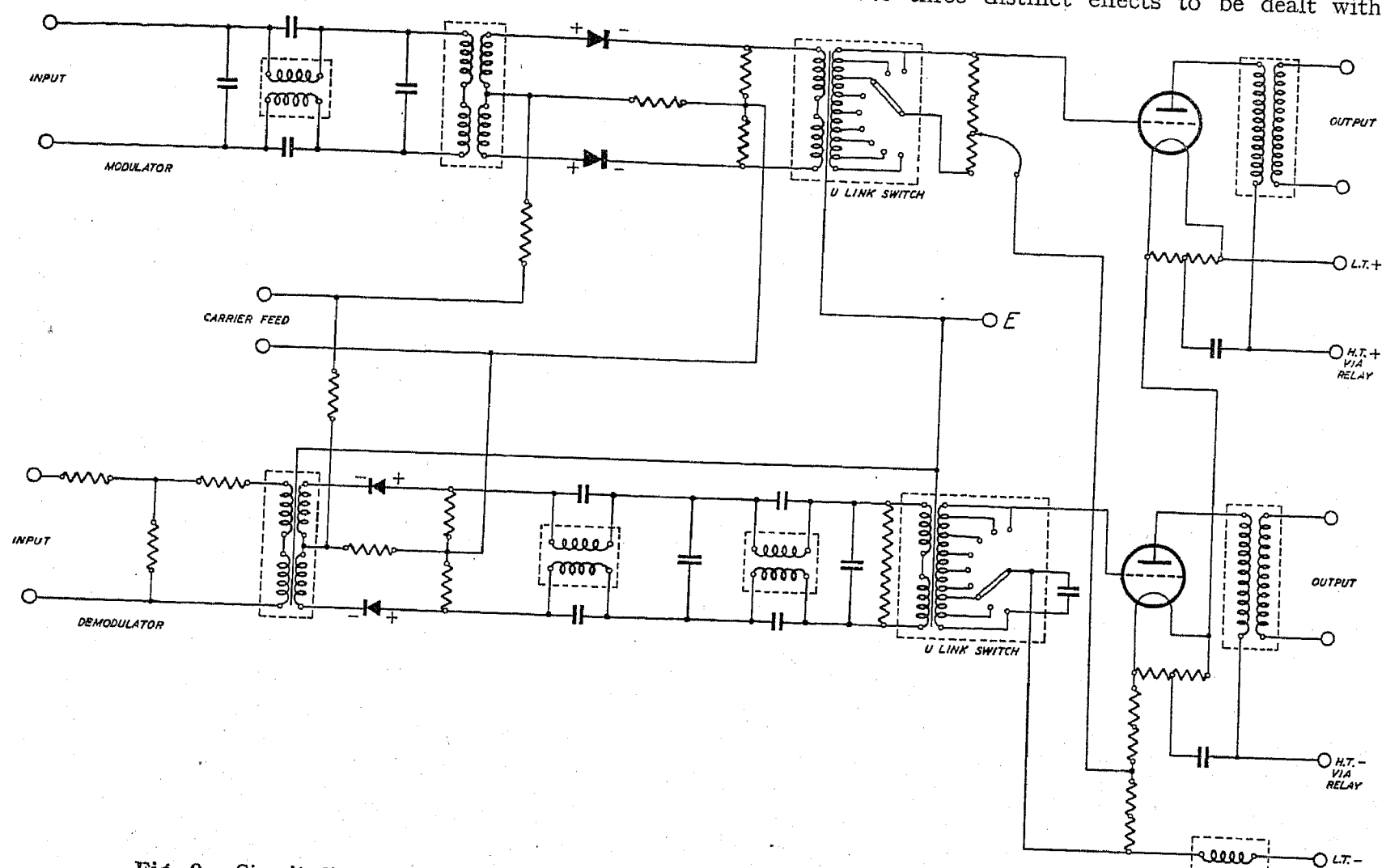
There are three distinct effects to be dealt with:

Fig. 9.—Circuit diagram of modulator and demodulator for single-channel 4-wire carrier system.

Fig. 9 shows the modulator and demodulator. The filter before the modulator cuts off the higher audio frequencies which would pass through the modulator and carrier filter and distort the side-band. The two rectifiers in the modulator are balanced so that the carrier is suppressed as in a Carson push-pull modulator. The demodulator is very similar, and both are usually adjusted to convert audio to carrier frequency (and vice versa) without amplification. When echo-suppressors are used they are placed at one terminal, on the office side of the line filters. If they were placed at an intermediate repeater it would be necessary to divide the audio-frequency and carrier channels by means of filters. Suppressors of the valveless type work satisfactorily as terminal suppressors, and the one associated with the carrier channel operates, on one side, from the demodulator, enabling the latter to be operated

(i) Audio—carrier disturbance (harmonics). (ii) Carrier—audio disturbance (rectification). (iii) Modulation of carrier side-band by audio-frequency currents passing through repeaters at the same time.

Only the last is strictly cross-modulation, since it is due to the formation of side-bands when the audio and carrier frequencies are together subject to non-linearity of valves or loading coils. This effect does not occur during silent intervals on the carrier channel, since the carrier is suppressed, and it is only apparent as a distortion of the wave-form of the speech. Fortunately it has proved quite negligible in practice. A series of articulation tests was made, in which the percentage of logatoms (meaningless monosyllables) correctly received over the carrier channel was found to be the same whether or not loud speech was being transmitted on the audio-frequency channel.

As regards the first type of disturbance, cross-talk from the audio-frequency to the carrier channel is due to harmonics of speech which fall within the frequency range of the lower side-band. The most troublesome is usually the 3rd harmonic of the dominant frequency (1 100 to 1 200 per sec.) in telephone speech. In the other direction, from carrier to audio, the side-band frequencies are partially rectified and give rise to frequencies in the audio range. The resulting noise is quite unintelligible, though it has the same rhythm as speech. These two effects can be reduced by adjusting the repeater levels to such a value that overloading sufficient to produce grid current never occurs, and only the slight non-linearity of the valve characteristic remains. As soon as grid current flows, the percentage of harmonics in the speech rises sharply and causes a harsh sound to be heard in the carrier channel. The greater the input transformer ratio the more severe is this effect, as the grid-filament impedance is stepped down to a lower shunting impedance at the input of the repeater. Evidently, therefore, one way in which this grid-current effect may be reduced is to use an input transformer with a low ratio, as in the case of the 2-stage main-line repeaters used in this country. Moreover, the peaks of unusually loud speech may be cut off (without detriment to its quality) by means of a " limiter " consisting of metal rectifiers arranged to shunt the input of the audio-frequency circuit for (instantaneous) speech voltages exceeding, say, 2 volts. In the ordinary way repeaters in voice-frequency circuits are overloaded by the peaks of very loud speech, but not to such an extent that the quality is appreciably affected. This high speech volume invariably means that the speaker's microphone is producing very severe non-linear distortion, particularly at frequencies near 1 100 cycles per sec. (the usual resonance point of the diaphragm), so that the ear is, on the whole, favourably affected by the suppression of the higher peaks, some of which may almost be regarded as acoustic shocks.

The limiter is introduced to provide for the exceptional cases where very loud speech occurs almost directly at the end of the trunk circuit. In order to deal with cross-talk in the other direction it is advisable, in addition to the adjustment of output levels to zero, to compensate the curvature of the valve characteristic by means of a metal rectifier shunted by a suitable resistance. The combination is put in series with the repeater output, and introduces a 2nd harmonic which cancels that generated in the valve. It does not, however, compensate the harmonic produced by grid current, and has no effect on audio-to-carrier cross-talk. Conversely a limiter is of no great value at the input of the carrier channel, as the modulator itself acts as a limiter. Details of the limiter and compensator are shown in Fig. 10.

Cross-modulation from audio to carrier is also caused by hysteresis in the loading coils. Even with the modern dust core the effects of hysteresis are felt, on long lines, as an increase of attenuation with current, due to increased effective resistance of the coils. The attenuation is approximately $\frac{1}{2}R\sqrt{(C/L)}$, where R = total resistance per mile, C = capacitance, and L = inductance.

The increase in coil resistance is, for the very small currents occurring in practice, so small as to be difficult to measure on a single coil. The total effect on the attenuation of a line is, however, sufficient to give cross-talk of the same order as that from carrier to audio.

The increase of hysteresis resistance per milliamp. depends on the size and material of the core. For the same material, increasing the size of core while retaining the same inductance reduces flux density and therefore hysteresis resistance. At a given frequency the resistance-increase per milliamp. per henry is $K\sqrt{L}$, where L = inductance of coil. For the main-line coils now used by the Post Office, $K = 10$. Somewhat larger coils, used when carrier-current working is required, have $K = 6$. Cores of specially treated pure iron dust are available for which $K = 1$. These have been used for filter inductances but not for loading coils, in this country at any rate.

In Fig. 11 the three curves show the variation of both types of cross-modulation with repeater output level. They were taken by means of aural comparison, the

VOLTAGE LIMITER

REPEATER OUTPUT VALVE — LINE TRANSFORMER
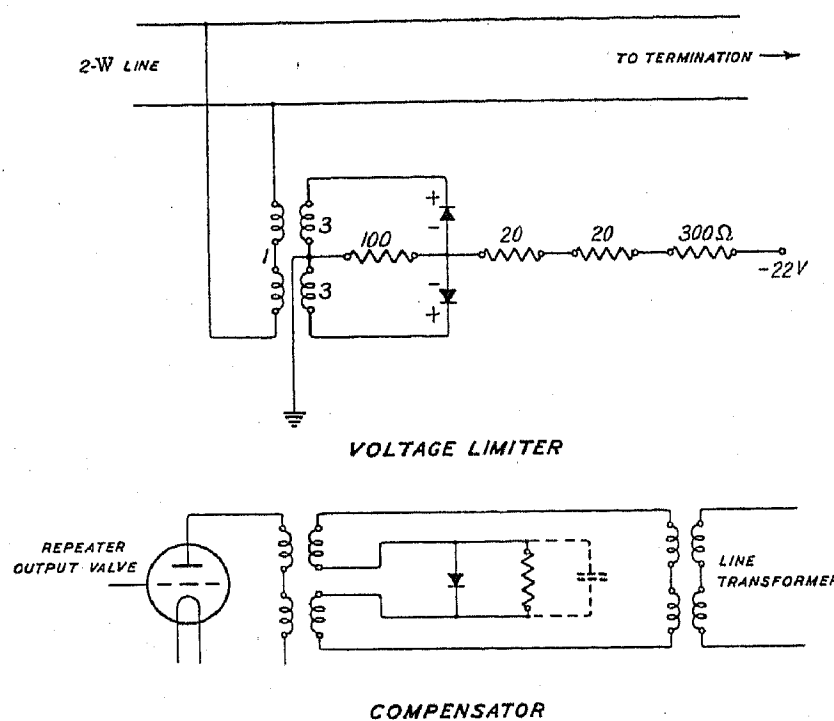
COMPENSATOR

Fig. 10.—Voltage limiter and compensator for cable carrier system.

loudness of the unintelligible cross-modulation being balanced against the speech producing it. The effect of the loading coils (in this case having $K = 20$) is seen to be the dominant factor in audio-to-carrier disturbance, but provided the repeater output level is zero both forms of disturbance are more than 55 decibels below the speech. This signal/noise ratio is found satisfactory in practice where the disturbance consists of intelligible speech. For the quite unintelligible disturbance now being discussed it is therefore safe to allow a signal/noise ratio of 50 decibels. In measurements, the loudest speech volume (" reference volume ") which ever occurs at the input of a trunk line, is used. In 90 per cent of conversations, however, the speech volume is at least 6 decibels less, corresponding to a signal/noise ratio 6 decibels better. The disturbance has the rhythm of speech but is different in quality. Thus it is almost impossible to make a consistent aural

comparison with speech or with a steady tone. The result depends on individual judgment, and may vary as much as 20 decibels between two observers.

A method of testing which eliminates this variation,

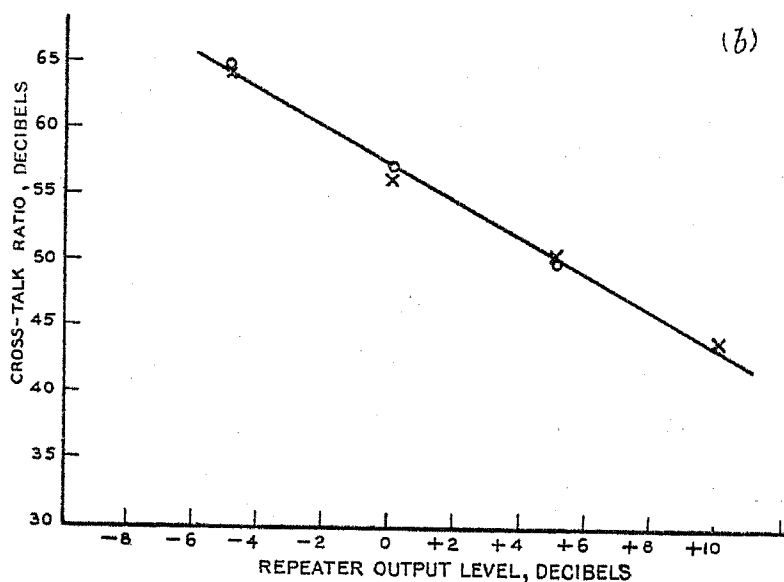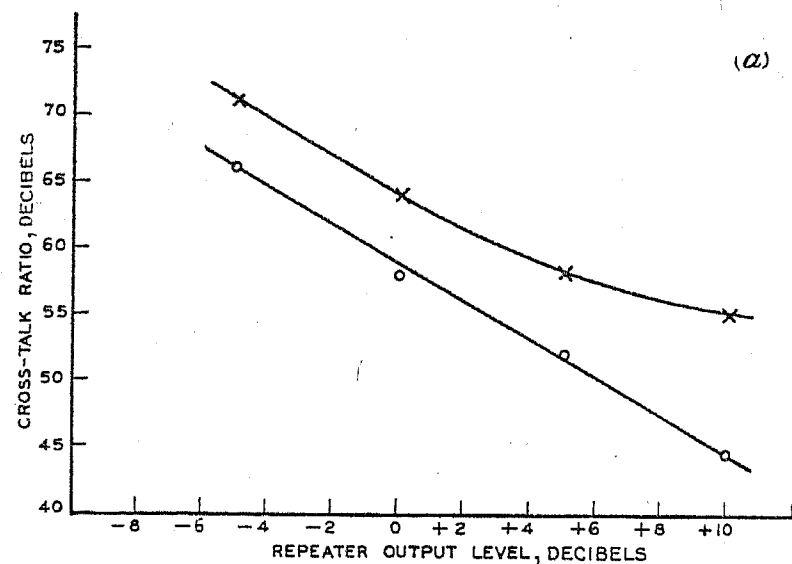a drum which can be rotated before a photocell in such a way that speech of known volume is applied to the circuit under test while typical disturbance, and the actual disturbance caused by the speech, are presented alternately to the listener by means of relays. It is an easy matter to balance the loudness of these two noises, with the aid of a variable attenuator, within 1 decibel.

The arrangement is used for studying the effect of alterations in repeaters, filters, etc., and checking the cross-modulation of complete systems. A considerable amount of research has yet to be done on cross-modulation in repeaters, both single- and double-stage, and the laws of addition applicable to cross-modulation in a number of consecutive repeaters have yet to be confirmed. When this carrier system was first tried it was thought that special repeaters, with a large distortionless output, would be necessary, such as the music repeaters designed for broadcast programme transmission.* The use of limiters and compensators in conjunction with ordinary repeaters is satisfactory, however, and much more economical.

The level diagram of a typical 4-wire audio and carrier circuit between London and Glasgow is given in Fig. 12. It will be noticed that there are four single-stage "toll" repeaters in the circuit. As the circuit is in the recently converted "Northern Underground," one of the oldest telegraph cables, the conductors are of 100 or 150 lb. per mile and consequently give attenuations of only 20 decibels or so between repeater stations. A cable cross-talk attenuation of about 75 decibels at 5 000 cycles per sec. could therefore be tolerated, allowing a minimum signal/noise ratio of 55 decibels on "zero" circuits. The relevant frequency in the carrier range is in the neighbourhood of 5 000 cycles per sec., being the lower side-band produced by modulating the 5 800-cycle carrier with a frequency of 800 cycles per sec., because the greater part of the energy of ordinary telephone speech lies in the range 800–1 200 cycles per sec. The formation of the cable is such that, for most of the way between London and Glasgow, each 4-wire circuit occupies a quad.

Fig. 11.—Carmarthen–Haverfordwest cross-modulation tests.

(a) Carrier to audio.
(b) Audio to carrier.
O With common amplifiers.
× With separate amplifiers.
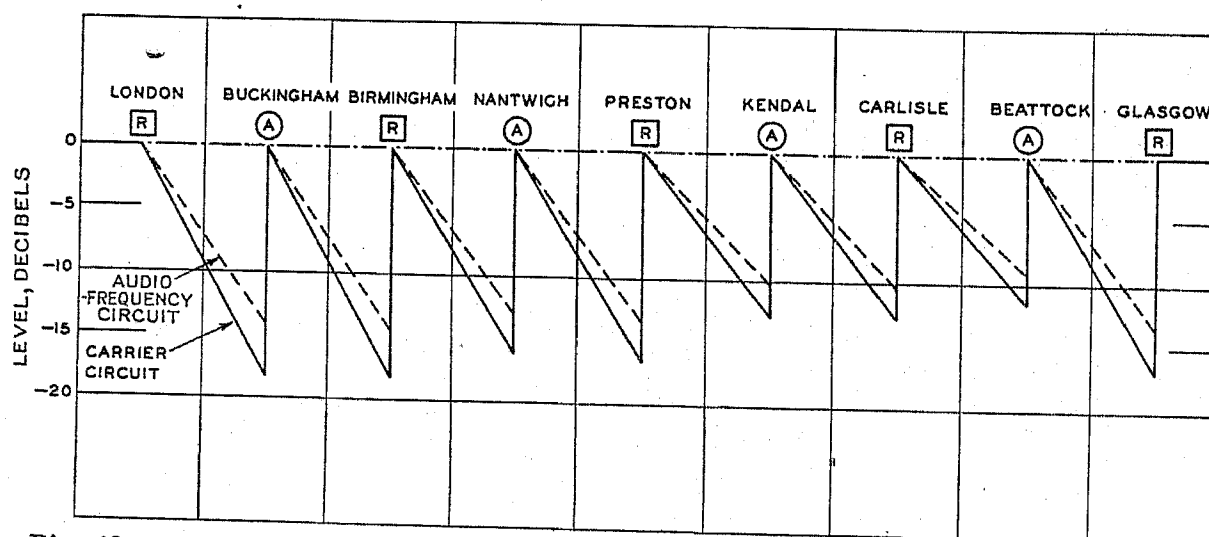
Fig. 12.—Level diagram for London–Glasgow 4-wire audio-frequency and carrier circuits.

and enables results to be repeated at any time, has therefore been developed. Records were made on sound film of (i) speech, (ii) audio-to-carrier disturbance, and (iii) carrier-to-audio disturbance. The film is mounted on

It is of the greatest economic importance to decide on the practical limit of cross-talk attenuation for long

* A. C. TIMMIS and C. A. BEER: "Underground Circuits for Transmission of Broadcast Programmes," Post Office Electrical Engineers' Journal, 1931, vol. 23, p. 315.

telephone circuits. This may be emphasized by quoting an example from the London–Leeds cable. A comprehensive series of tests showed that raising the cross-talk limit from 52 to 56 decibels in one repeater section would have meant rejecting 16 out of 26 workable carrier circuits between London and Leeds.

The disturbing effect of cross-talk is twofold. It may (i) reduce the intelligibility of speech on the disturbed circuit, this effect depending on the signal/noise ratio; or (ii) it may be heard as more or less intelligible speech on the disturbed circuit during a silent interval. This latter effect depends on the absolute level of cross-talk, which in turn depends on the loudness of the disturbing speech and the measured cross-talk attenuation.

Experience shows that, if this cross-talk attenuation (usually termed simply "cross-talk") is at least 55 decibels, the chance of loud speech on the disturbing line being overheard to an appreciable extent on the other line is so small that it may safely be neglected. The first effect, measured by the increased repetition rate* on the disturbed line during conversation on the disturbing line, is quite negligible even for cross-talk as low as 48 decibels. Evidently, therefore, in the case of telephone lines, the first effect is not the criterion of tolerable cross-talk.

In well-balanced modern cables a suitable degree of cross-talk can be obtained at audio frequencies between quads in the same group. At low carrier frequencies, such as 5 000 cycles per sec., it can only be obtained by separating the go and return pairs by a concentric screen of metallized paper, or by layers of quads used for audio-frequency circuits. To enable higher carrier frequencies to be used, so that multi-channel carrier systems may be applied [to [cables, a much higher standard of cross-talk is necessary, for two reasons. First, very light loading, if any, must be used to allow of a high cut-off frequency. Hence the attenuation of reasonably heavy conductors is high, and gains must be as high as practicable to keep down the number of repeaters. Secondly, the magnitude of cross-talk, both electrostatic and electromagnetic, increases more or less proportionally with frequency. One obvious method of obtaining the necessary degree of separation is to work the go and return pairs in separate cables. This is very effective. Even if the cables are in adjacent ducts, there is no measurable cross-talk between them up to 50 kilocycles per sec. Within each cable, far-end cross-talk (between "go" and "go," or "return" and "return") can be dealt with by inserting crosses, and by means of coupling circuits. The latter method was recently used in America, when an experimental multi-channel carrier system was set up at Morristown by the American Telephone and Telegraph Co. The same method, applied to near- and far-end cross-talk, was first tried by the Post Office in 1927, having been developed in 1926 by the late C. Robinson.

If a single-frequency tone be applied to one pair and the cross-talk observed on another, it is generally an easy matter to find some values of resistance and capacitance in series which, when connected between one wire of the first pair and one wire of the second, will balance out the cross-talk. The process may be repeated for a large number of frequencies, and a curve of balancing impedance against frequency may be prepared for that part of the range in which most of the energy of telephone speech occurs, say from 600 to 1 500 cycles per sec. For near-end cross-talk this curve generally has severe undulations, and requires a network of resonant circuits to simulate it accurately. A method of designing such a network was completely worked out, but was never applied in practice. It was found, from measurements of near-end and far-end cross-talk at various frequencies, that correction of the near end was apt to increase the far-end cross-talk. This does not apply to 4-wire working in separate cables or groups, however, where the coupling circuits are only required for neutralization of far-end cross-talk; and, since the phase change in any far-end cross-talk path is the same, the cross-talk/frequency curve is comparatively smooth. Hence the problem of neutralizing is much easier, in both the audio-frequency and the carrier-frequency range.

Balanced carrier working on 2-wire circuits is scarcely practicable on account of the difficulty of maintaining accurate balances at high frequencies; but it is quite possible to combine 2-wire audio working with the single-channel 4-wire carrier system already described, using the same repeaters to amplify both audio-frequency and carrier currents.* The principle will be clear from Fig. 13.

It is necessary to use 2-wire repeaters on each pair, but to prevent singing at the higher audio frequencies and restrict the carrier currents to one half of each repeater a low-pass filter is inserted in the "up" side amplifier in one pair and the "down" side amplifier in the other. In the unfiltered half of any intermediate repeater the same limitations are imposed by cross-modulation as in the 4-wire audio and 4-wire carrier system. Limiters and compensators, together with a restriction of repeater output level to zero for both audio and carrier currents, enable the far-end cross-talk (or cross-modulation) to be kept down to satisfactory values.

There are certain forms of cross-talk possible at the terminals, however, which must be guarded against by special means. In Fig. 13 only one intermediate repeater station is shown for simplicity. The terminal equipment at the right-hand side of the diagram includes a terminal repeater for each audio-frequency circuit, and a single-stage amplifier to raise the input level of the demodulator, so that all three circuits may be adjusted to zero overall equivalent. (If common repeaters were used for audio and carrier circuits the output level would be limited to zero, and the overall equivalent of the circuits would be at least 4 decibels, the loss through one hybrid coil.) At the left-hand side of the diagram, terminal echo-suppressors are shown. An amplifier before the modulator, in conjunction with the amplifying valve in the demodulator, enables a valveless echo-suppressor to operate on the carrier channel. The filters PP prevent the higher speech frequencies, above the useful range, from passing round the hybrid coil H —which is not accurately balanced for such frequencies

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* The number of repetitions asked for per 100 sec., due to imperfect reception, is used as a criterion of quality of transmission.

* British Patent No. 431010.

—and entering the demodulator, whence they would appear as cross-talk on the carrier channel. The filter is preferably placed before the associated amplifier because the impedance which the hybrid coil H presents to the carrier current is then approximately equal to that of the line, and there can be no appreciable reflection to cause frequency distortion in the carrier channel.
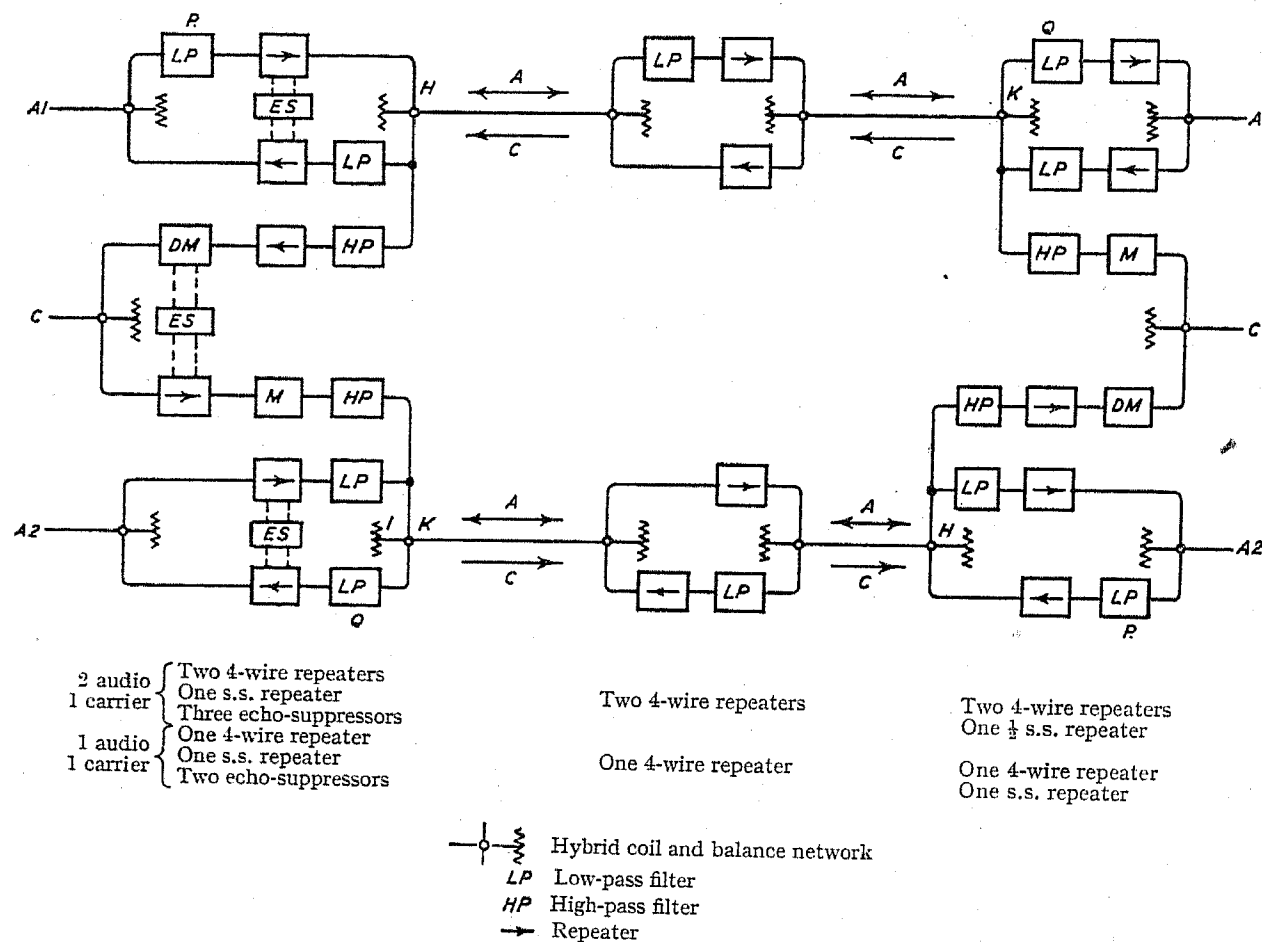
The filters QQ are required to prevent near-end carrier-to-audio cross-talk through carrier currents from the modulator passing round the hybrid coil K and through the upper half of the repeater, where they would be partially rectified and so be heard on the audio-frequency channel. The filter is placed before the amplifier to avoid rectification of the carrier therein. All the balances are made as good as practicable in the

(h) Future Developments

In the near future, long trunk cables of the type now used will probably contain a mixture of audio-frequency and carrier circuits, the latter working on different systems according to their length.

It has recently been proposed to use special cables of the concentric or screened-pair type to provide a large number of carrier-frequency channels. The negative feed-back amplifier, which can handle many carrier channels without cross-modulation, is an essential feature of the scheme.*

For the longer trunk circuits, the 4-wire principle seems likely to be retained because of its two great advantages—stability over the whole working frequency range, and independence of line impedance. Although,

2 audio 1 carrier { Two 4-wire repeaters / One s.s. repeater / Three echo-suppressors

1 audio 1 carrier { One 4-wire repeater / One s.s. repeater / Two echo-suppressors

Two 4-wire repeaters

One 4-wire repeater

Two 4-wire repeaters
One ½ s.s. repeater

One 4-wire repeater
One s.s. repeater

—⊙—⧚ Hybrid coil and balance network
LP Low-pass filter
HP High-pass filter
—▸ Repeater

M = modulator. DM = demodulator. ES = echo-suppressor. s.s. = single stage.

Fig. 13.—Carrier working on 2-wire audio-frequency circuits.

carrier range, in order to assist the discrimination of the low-pass filters.

The application of the system in practice depends mainly on the conditions for working 2-wire audio-frequency circuits. With the light loading required for carrier transmission the attenuation of a normal repeater section may be high, necessitating 2-stage repeaters, but high singing-points should also be obtainable, so that long 2-wire circuits with an equivalent approaching zero should be possible.

The system has been applied experimentally to part of the London–Edinburgh (East Coast) cable, in which the pairs are loaded for side circuits only. In cases where the phantoms are loaded, three audio-frequency circuits per quad may be worked. The carrier channel does not affect the phantom in any way.

by the use of stabilizers, very long audio-frequency 2-wire circuits can be worked at zero equivalent and made less sensitive to changes of impedance (such as the insertion of a length of interruption cable) in the neighbourhood of the stabilizer, they can never be quite so robust as 4-wire circuits.

(3) SEA CABLES

The modern sea cables maintained by the British Post Office may be divided into three main types:—(a) Continuously loaded, paper-core, lead-covered; such as the Anglo-Dutch No. 3 cable. (b) Non-loaded gutta-percha or balata core; such as the Isle of Man–Ireland cables.

* L. ESPENSCHIED and M. E. STRIEBY: "Systems for Wide-Band Transmission over Coaxial Lines," Bell System Technical Journal, 1934, vol. 13, p. 654.

(c) Non-loaded, screened, paper-core, lead-covered; such as the Anglo-French (1933) cable.

For reasons which are outside the scope of this paper, neither the coil-loaded nor the concentric type is much used round these shores. The former is used extensively in the Baltic, and the latter is the type most suitable for very deep waters.

The Anglo-Dutch No. 3 cable contains 4 quads (16 wires). On account of the symmetrical arrangements and continuous loading, the phantoms and super-phantoms are all of reasonable attenuation and their complete utilization enables 16 circuits to be worked. A single-channel 4-wire carrier system is working on each quad, giving 4 more circuits. The carrier frequency is 5 800 cycles per sec., as in the system described for land cables.

The installation at Ballyhornan is of special interest because it is housed in an unattended station, visited only once a week for battery charging, and the apparatus is enclosed in steel boxes with a quantity of silica gel to absorb moisture. Although cable huts are apt to be damp, owing to condensation of sea mist, etc., the apparatus has worked perfectly well for over a year. In order to economize battery power, valves taking 0·15 amp. at 4 volts are used, and relays are arranged to operate alarms at Belfast in case of valve failure, so that time is not wasted in localizing the trouble, and a lineman is immediately sent to Ballyhornan to deal with it. At Blackpool repeater station the normal battery supplies are used. At Port Erin (Isle of Man) the carrier circuit passes through a 4-wire repeater, with special equalizers.

ENGLISH LAND CABLE (UNARMOURED)

FRENCH LAND CABLE (TAPE - ARMOURED)

Lead-Antimony-Cadmium alloy sheath (0·5 % Anty - 0·25 % Cadm) Min. thickness 0·100"

Overall diam. 1·55"max.

Overall diam. 2·10"max.

2 lappings of Paper, 1·58"wide, 0·0045"thk. with final lapping of selvedge tape 1⅞"wide

2 Steel tapes 0·030"thick

19 Screened Quads (1+6+12) Diam. over centre 0·235"approx. " " 1ˢᵗ layer 0·80" " " 2ⁿᵈ " 1·26"

Diam. of Conductors, 0·064"- 0·065" Paper string, 0·015"- 0·018" with ⅝" lay 1ˢᵗ Paper ⅜"x 0·0035" 2ⁿᵈ " ½"x 0·0035"(marked)

Over Quad:— 2 lappings of Paper 1ˢᵗ Undyed, ¾"x 0·0055" 2ⁿᵈ Coloured as spec., ⅝"x 0·006" and screening metalized paper, ⅞"x 0·0025"

Lead-Antimony-Cadmium alloy sheath (0·5% Anty - 0·25 % Cadm), Min. thickness 0·13"

25 No.2 S.W.G. "Homo" wires

2 Thicknesses of Duck Tape 6 " " Rubber Tape 2 " " Duck Tape (Min. thickness 0·2")
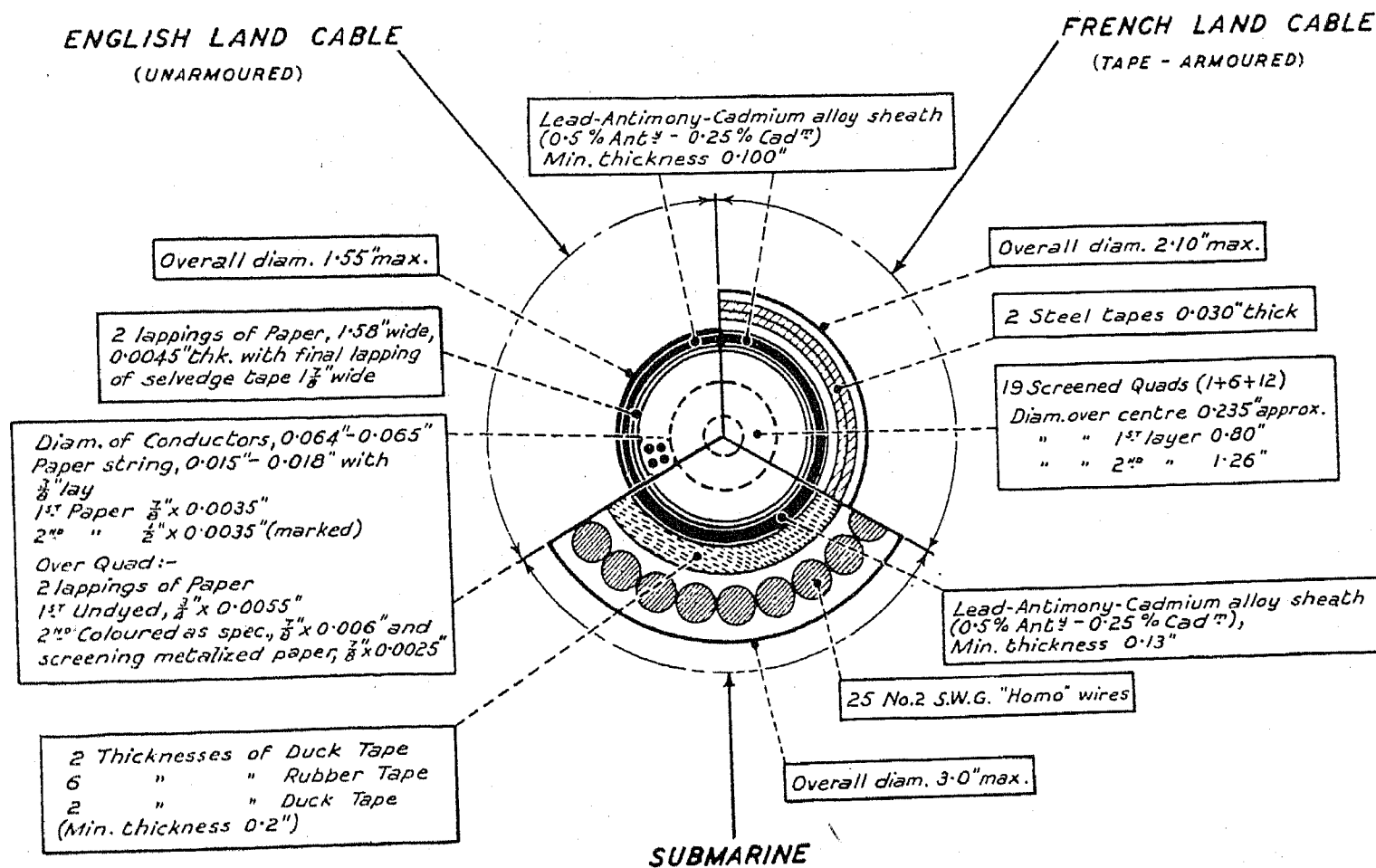
Overall diam. 3·0"max.

SUBMARINE

Fig. 14.—Anglo-French (1933) cable.

It is intended to equip the Irish cable route via the Isle of Man fully with carrier circuits in the near future. A temporary single-channel system is now working. Between Blackpool and the Isle of Man the cable is a 4-quad, continuously loaded, lead-covered paper type similar to the Anglo-Dutch No. 3 cable. Owing to rising attenuation the single-channel system is the only practicable one for this cable. There are two cables between the Isle of Man and Ballyhornan (Northern Ireland), both of the 4-core balata type without the usual anti-teredo brass tape. The omission of this tape reduces the attenuation at high frequencies considerably, and it is practicable to work a 4-channel, 4-wire, carrier system on each cable. The cable "hut" at Ballyhornan was built for the accommodation of carrier apparatus and the necessary power plant. Thence to Belfast there is a cable loaded for audio frequencies only.

The permanent carrier apparatus at Blackpool will be practically the same as that already described for land cables, one carrier channel being worked on each quad of the loaded cable. At Port Erin and Ballyhornan, 4-channel carrier equipment will be required for each cable. The design is complete, having been based on experimental work and trials of a 2-channel system between Port Erin and Ballyhornan. The carrier frequencies are 6·0, 9·15, 12·5, and 16·0 kilocycles per sec. Thus, when the route is fully equipped with carrier channels, there will be 4 carrier circuits between Blackpool and Port Erin, and 8 between Port Erin and Ballyhornan.

The Anglo-French (1933) cable was the first non-loaded paper-core sea cable laid in the Channel. A cross-section of the cable is shown in Fig. 14. The length being only 26 nauts, it was found practicable

to obtain reasonable attenuation at the lower carrier frequencies. Owing to the absence of loading, and to the accuracy of manufacture, this cable proved extraordinarily good in respect of cross-talk.

The 19 quads are each screened with metal-sprayed paper, and the cross-talk between pairs in different quads and from phantom to phantom is so satisfactory that it is possible to work a 4-wire single-channel carrier system, on side and phantom circuits. Typical audio-frequency figures (in decibels) are the following:— Side—side (same quad) far end, 108. Side—phantom (far end), 97. Phantom—phantom (near end), 128. Pair—pair (near end in different quads), 122.

The attenuation of side circuits at 1 000 cycles per sec. is 20 decibels, and at 5 000 cycles per sec is 32 decibels.

It is therefore advantageous to use the 18 sides and 9 phantoms of 9 quads as go circuits and the sides and phantoms of 9 other quads as return circuits, leaving the centre quad to be dealt with specially. Thus we obtain 27 4-wire circuits, apart from carriers. The cross-talk at carrier frequency easily allows one 4-wire carrier to be superposed on each physical and phantom 4-wire circuit, giving another 27 speech channels. One audio-frequency and one carrier channel can be worked on the centre quad, making a total of 56 speech channels, all 4-wire circuits.

The cross-talk within a quad is so slight that it would appear quite practicable to work two 2-wire audio-frequency circuits instead of one 4-wire in each of 18 quads. Very accurate balances could be made at the ends and, with 4-wire circuits on the land, overall equivalents of zero could be obtained. This would bring the total number of circuits up to 56 + 18 (= 74), without reckoning one or two double phantoms. The carrier system will be practically the same as for single-channel working on land cables, but the repeaters have special equalizers to deal with the attenuation of the non-loaded cable.

The success of the Anglo-French (1933) cable is largely due to the screening, which has resulted in very good cross-talk figures; and in the design of future sea cables, whether paper- or balata-insulated, screening may play an important part.

A certain amount of research work has been done by the Post Office regarding screens at frequencies up to 50 kilocycles per sec., and the results may be very briefly summarized thus: In a paper-core cable a very thin screen (such as metallized paper) gives almost complete electrostatic protection. In a gutta-percha cable the sea water surrounding the cores acts in a similar way. Electrostatic screening, however, does not sufficiently reduce cross-talk at high carrier frequencies. The residual effect, which is electromagnetic, can be reduced by the use of heavy copper-tape screens, 0·016 in. or more in thickness. The thicker the screen and the higher its conductivity, the less the effective resistance (and therefore attenuation) of the conductors. Copper is the best material for high frequencies. An approximate theory of the eddy-current and magnetic screening effects is given in the Appendix.

The British Post Office maintains considerably more submarine telephone cables than any other adminis-

tration, but whether this number is likely to increase in the next few years is an interesting speculation. Short-wave radio links constitute a formidable rival for such distances as England to France and Scotland to Ireland. If, however, the sea cable of the future were buried in a trench (as some of the Atlantic telegraph cables now are, off the Cornish coast) it could almost achieve perfection in regard to both reliability and secrecy.

In conclusion, the author wishes to thank the Engineer-in-Chief of the Post Office for permission to publish this paper, and to acknowledge his indebtedness to the various colleagues who have assisted, directly and indirectly, in its preparation.

APPENDIX

Eddy-Current Losses in Screened Conductors

Screened conductors in telephone cables are generally made up in either pairs or quads. Eddy-current losses occur in the wires themselves (skin effect) and in the other wires of a quad, but in the case of screens heavy enough to give appreciable electromagnetic screening effect the eddy currents therein are responsible for the greater part of the effective, or incremental, resistance.

A simple analysis of the screen losses may be made, by regarding a short length as a loosely coupled transformer with a loaded secondary. The core forms the primary, and the screen the secondary, for this equivalent transformer.

Let M = mutual inductance, m = coefficient of mutual inductance, L_1 = inductance of primary, R_1 = resistance of primary, L_2 = inductance of secondary, R_2 = load resistance across secondary, V_1 = voltage impressed on primary, i_1 = primary current, i_2 = secondary current.

Then, by solving the mesh equations, the primary impedance is obtained in the form

$$Z_1 = \frac{V_1}{i_1} = \left(R_1 + \frac{\omega^2 M^2 R_2}{R_2^2 + \omega^2 L_2^2} \right) + \left(j\omega L_1 - \frac{j\omega^3 M^2 L_2}{R_2^2 + \omega^2 L_2^2} \right)$$

The incremental resistance due to the secondary (screen) is therefore $\omega^2 M^2 R_2/(R_2^2 + \omega^2 L_2^2)$, and for a given frequency this is a maximum when $R_2 = \omega L_2$. The resistance is then $\omega^2 M^2/(2R_2) = \omega M^2/(2L_2) = \omega m L_1/2$. The decremental inductance due to the secondary is $\omega^2 M^2 L_2/(R_2^2 + \omega^2 L_2^2)$, and for a given frequency this always increases as R_2 decreases, until it reaches a limiting value of $M^2/L_2 = m^2 L_1$ when $R_2 = 0$. This condition corresponds to perfect electromagnetic screening and complete destruction of the leakage flux. Thus it is important to note that low screen losses can be consistent with a high degree of electromagnetic screening. From the foregoing simple conception of screen losses it is evident that:—

(a) For any given frequency, the incremental resistance will have a peak value for some particular resistance (or resistivity) of the screen, the value being zero both for zero resistivity and for infinite resistivity. The material of the screen does not matter; the resistance

only is of importance. Thus low screen losses can be obtained with either a very thin or a very thick screen.

(b) Although a very thin screen (metal-sprayed paper, for instance) may give adequate electrostatic screening, it will clearly be necessary to use a thick screen to obtain adequate electromagnetic screening.

(c) **The lower the resistance of the screen** [which, in terms of (b) above, corresponds to the most efficient screening] the greater will be the decremental inductance. There is, however, a limiting value of the decremental inductance for a given cable geometry, namely m^2L_1. Since the coefficient of mutual inductance m depends only on the cable geometry, the limiting decremental inductance depends solely on the same.

(d) The value of m^2L_1 having been established, either by measurement or by calculation, it is possible to write down the maximum incremental resistance which can be caused by the screen at any particular frequency. The locus of these maxima on a frequency base is a straight line through the origin—$R = mL_1/2$—if the primary self-inductance is constant.

The above analysis is due to Mr. R. J. Halsey. The general conclusions arrived at above were confirmed by a rigorous analysis of screen losses based on Maxwell's electromagnetic equations, made by Mr. H. J. Josephs. The curves of Fig. 15 were obtained by measurement, and agree in general form with the results of calculation.
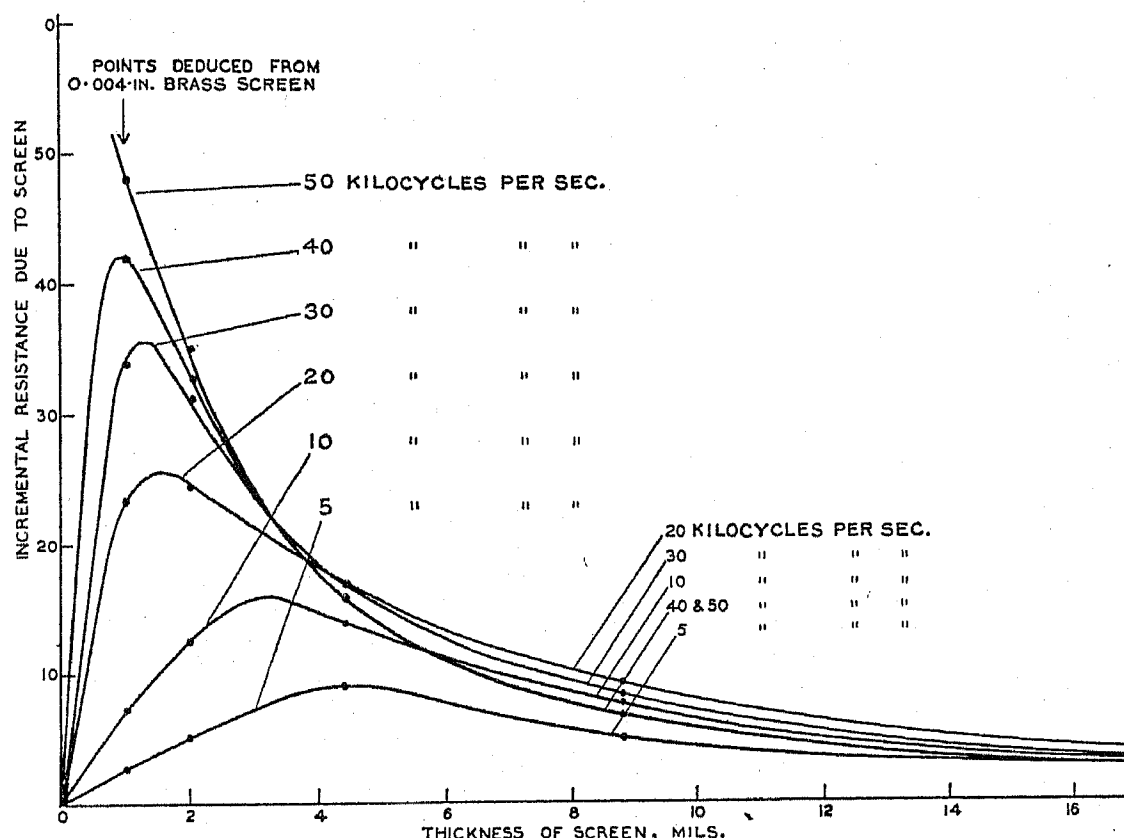

Fig. 15.—Incremental resistance of quad cable due to copper-tape screens.

DISCUSSION BEFORE THE INSTITUTION, 16TH JANUARY, 1936

Mr. F. Gill: The longest distance shown on the map (Fig. 1) is about 600 miles, whereas I suppose that to most of us the term "long-distance telephony" connotes continental lengths, i.e. distances up to about 7 000 miles. India, from north to south, is about 2 000 miles in length. In the U.S.A. the distances are greater, and there are lengths of about 2 000 miles of open-wire lines; in Australia, the lengths are up to about 4 000 miles. It is difficult to see any immediate hope that such lengths will be served by cable in countries where the population is sparse and the revenue low, and, this being so, the aerial-line carrier system cannot be dismissed quite so lightly as the author dismisses it.

I find it rather difficult to visualize single-channel carrier systems for very long distances. It seems to me that, for long aerial lines, multi-channel systems must be adopted on economical grounds.

In regard to the question of mains-operated repeaters; in the case of the ordinary repeater we do not rely

entirely on the public supply; we have batteries, and the necessary charging equipment. If, however, we take the risk of relying entirely on a public supply, then we can effect a saving in first-cost. If, at this risk, mains operation can be used for single-channel systems, may it not also be used for multi-channel?

The author says in the Summary that the growth of international telephony has been rapid since the advent of the thermionic valve, but I do not think the two events are closely connected. Chicago and New York, cities 750 miles apart, were in commercial connection 43 years ago, when there was no thermionic valve. It was in 1925—10 years after the thermionic repeater had been put into commercial service—that the rapid growth began. It was not the technical means, it was organization, which had previously been lacking in international telephony

As a reminder of how recent international telephony is, I would mention that in 1928, roughly 3 years after

the growth had begun to make itself manifest, only about 30 per cent of the possible connections had been made between 34 of the principal cities in Europe.

Lieut.-Col. A. G. Lee: This paper deals with the past developments in audio-frequency telephony, and with what I might perhaps call the fringe of the carrier development. I propose to make a few remarks on future carrier development.

The carrier circuits outlined by the author amount to one, two, or a few more, carrier circuits per physical audio circuit; whereas the vision which we see now is one of a large number of carrier circuits on a physical circuit, or the system referred to by Mr. Gill as multi-channel operation. Two cables have recently been laid between Bristol and Plymouth, so arranged that the " go " speech travels on one cable and the " return " speech comes back on another. By thus separating the go and return channels one can avoid a certain amount of cross-talk, and make possible a larger number of carrier channels on each physical circuit. We hope to get up to 12 carrier circuits on each physical circuit, so that the 19-pair cables will give us 228 channels each.

A further development is in progress. Standard Telephones and Cables, Ltd., are laying at the present time a cable between London and Birmingham of the coaxial type, which has been developed experimentally by the Bell Telephone Laboratories in America. It consists of a single concentric tube of $0 \cdot 5$ in. external diameter and an internal conductor of $0 \cdot 125$ in. diameter. These concentric tubes will be used as " go " and " return " for carrier circuits, and they will carry frequencies up to more than 2 000 000 cycles, i.e. what we ordinarily regard as the wireless range. We hope to get slightly over 300 carrier circuits per concentric core, but the actual number will depend on cross-talk and other considerations.

The economy of these new multi-channel methods depends largely upon the fact that a single repeater, consisting usually of about two valves, will carry all the telephonic conversations in carrier form that are put on the particular physical pair of wires. In the Bristol–Plymouth case, for example, one repeater will carry 12 conversations instead of there being a repeater allotted to each conversation. On the coaxial cable, a single 3-valve repeater will carry 200–300 telephone conversations. The stability and absence of cross-modulation of these repeaters are due to the application of the negative feed-back principle introduced by Black, of the Bell Telephone Laboratories.

Finally, with reference to the use of ultra-short waves for comparatively short-distance cross-channel communications, we have had 6 of these circuits in use for the last 12 months between Stranraer and Belfast. They have been included in the normal trunk communication system, terminating on the trunk switchboards at either end, and we have had no trouble whatever with them; the quality of the speech has been perfectly satisfactory. I hope that in the near future we shall have some of these circuits working across the English Channel to France, as an addition to the submarine cables. These carrier developments are all experimental at the present time, and, while we are quite sure we shall succeed in this development, the final use that we shall make of these circuits will depend on their cost. This we have not yet ascertained, because the equipments have not yet been made in large enough numbers.

Mr. A. W. Montgomery: The part of the paper which interests me most is that which deals with the subject of carrier working. It is a new subject, and yet an old one, for the telephone itself had its origin in voice-frequency carrier telegraph experiments. The author mentions that the single-channel carrier system has been designed with a view to the use of voice-frequency telegraphy over it at times in place of speech; I should like to refer to one interesting application of this sort. A 3-channel carrier telephone system, of the type mentioned in the early part of the paper as largely used on the Continent, operates between Capetown and Johannesburg, the distance (about 1 000 miles) necessitating 6 intermediate repeaters. On one channel there are at present working 12 voice-frequency telegraph channels, and the number is being extended to 18.

The author referred, in his introductory remarks, to the Tasmania cable. I think this is one of the most interesting recent applications of carrier working to a sea cable. The cable runs between Australia and Tasmania, and the existence of an island in the middle of the straits permits the use of a repeater station. The attenuation of each part of the cable at the highest frequency used is roughly 80 decibels, and the repeater station has therefore amplifiers which, allowing for equalization, give a maximum gain of 90 decibels. These amplifiers are of the negative feed-back type, and carry simultaneously the six channels which the cable provides. These are: one voice channel, two carrier channels operated on a balanced basis (advantage being taken of the smooth impedance curve), and three operated on a grouped frequency basis. There is in addition a single-way channel capable of carrying broadcast-quality music, this channel being switched either way as required.

The author mentions that the stabilized feed-back repeater has many advantages, one of which is the fact that voltage-changes have little effect on the repeater gain. This is a very useful property in actual operation, but it may be a rather inconvenient one in manufacture; for if an amplifier will apparently give the same results although abnormal conditions exist it may be difficult to determine whether it is as it should be or slightly faulty.

Mr. B. S. Cohen: The paper deals with the whole subject of the present position of telephony in the United Kingdom, and in view of the remarks of Mr. Gill I think this might form a better title for it.

I should like to refer to certain developments which have taken place in the 29 years since the paper with a similar title by Mr. Shepherd and myself was read before the Institution.* The loading coil was then just coming into general service, and only a short time ago it reached its zenith. At that time the British Post Office had several million pounds sterling invested in loading coils, but now the loading coil is rapidly disappearing from long-distance circuits and is in process of migrating from the line to the terminal apparatus. Take a case such as the 120-mile London–Birmingham line; one particular 4-wire voice circuit on this system has at present 210

loading coils. A similar modern circuit between London and Birmingham, using a 12-channel carrier with " go " and " return " cable circuits, would still require 50 high-grade inductances of low effective resistance and very low hysteresis loss (40 filter inductances and 10 equalizer inductances).

There is, however, one note of warning to be struck. Considerable progress has been made in substituting quartz crystals for the inductances in high-frequency filters; if the method can be extended below 100 kilo-cycles—and there are possibilities that this may happen in the future—there may be a slump in dust-core coils.

The future applications of multi-channel carrier systems, involving the laying of new and special types of cables, will be of tremendous importance, but sight must not be lost of the importance of the possibilities outlined in the present paper, e.g. that of providing a considerable number of additional channels over the existing networks by the use of such developments as 2-wire zero-loss circuits. Particular attention should be drawn to the system described by the author in connection with Fig. 13, whereby for each 2-wire circuit one can get a single carrier channel in addition. There is every indication that much better use could be made of the existing networks than has been the case in the past, by the utilization of recent advances in the art.

The author asks for a name to characterize the disturbances due to cross-modulation. It appears, however, questionable whether any advantage would be gained by adding still another term to the long series already existing. We have to consider three types of impairments, namely (1) Cross-talk, defined as conversation which is intelligible unless attenuated too much. (2) Cross-babble, or babble, i.e. conversation which is unintelligible at any level. (3) Cross-modulation effects, giving rise to various imperfections other than cross-talk or cross-babble. All these impairments are produced by two sorts of couplings, namely linear and non-linear.

Many of those who will read this paper but who are not working directly on the subject might find it useful to have a table dealing with some of these interactions between speech on one circuit or channel and another. This list might well include all the more important disturbances which result from audio—audio, audio—carrier, carrier—audio, and carrier—carrier couplings.

With regard to the statement that Great Britain has the largest number of submarine cables, I was surprised to find that in 1935 there were 45 000 circuit-miles of submarine cable owned by Germany, as against only about 20 000 owned by this country. We may have more cables, but the Germans seem to have more circuits, probably on account of the cables laid in the Baltic.

Mr. M. van Hasselt: It is stated in the paper that a carrier circuit may at times sing if connected to a subscriber's loop when the subscriber has not yet taken his receiver off the hook, and that in such circumstances there may be carrier howl on the circuit. I find the idea very disturbing, because if in the future the Post Office add more carrier systems to their lines such effects will become troublesome. Since a carrier circuit is very much like a 4-wire circuit, however, I find it difficult to conceive that this effect often occurs in practice. In this connection, I note that the author mentions a pos-

sible variation of the equivalent of the carrier circuit of 2 or 3 decibels. Taking a minimum distance of 30 miles, and an average distance of 100 miles, and assuming the loss on the line at the top carrier frequency to be of the order of 12 decibels, one would not expect a variation greater than $\pm 1 \cdot 2$ decibels. Has the author's figure of 2 or 3 decibels anything to do with the change in mains voltage?

Under the heading " Two-wire repeaters " (page 602) the statement is made that " The line attenuation permissible between 2-wire repeaters is now generally limited in practice by instability rather than cross-talk. . . . " On first reading this I got the impression that it was suggested that the stabilized repeater might be used on a large scale on 2-wire cable circuits to provide what are in effect 4-wire cable circuits; and I should like to ask the author whether he is satisfied that the position in regard to cross-talk obtaining in 2-wire groups on modern cables, especially from the point of view of babble, is in fact good enough to allow of a large-scale application. Or, on the other hand, does he think that the main application to audio-frequency circuits of the 2-wire stabilized repeater is in cases of 2-wire circuits proper, where it is desired to operate such circuits at a smaller loss than would otherwise be possible, and perhaps on older cables?

With regard to the cross-talk measured on open-wire lines where the construction is on the square, about 9 years ago we had occasion to measure the cross-talk on some lines in France in the neighbourhood of Bordeaux, where this form of construction is used and the cross-arms are of steel and two insulators in the same vertical plane are attached to a common bracket, which is clamped to the cross-arm, frequently out of truth. The cross-talk between circuits on the diagonals of the squares was so bad as to make the system unworkable, whereas that between circuits belonging to different squares was not excessive. We tracked down the trouble to irregular construction. It is well known that the cross-talk between two pairs on the diagonals of a true square is very small, but it becomes rapidly greater as the formation deviates from the true square.

Finally, I would suggest that in talking of intelligible cross-talk the expression " signal/noise ratio " is not the most desirable one to use, because the amount of cross-talk that can be tolerated under those conditions is entirely independent of the signal and depends solely on the efficiency between the point at which this cross-talk is measured and the subscriber's receiving apparatus. I suggest, therefore, that the expression " signal/noise ratio " is perhaps likely to be confusing, and that " cross-talk " pure and simple would be better.

Captain J. G. Hines: On page 601 the author makes a brief reference to the use by railway companies of 3-channel carrier systems on aerial lines, and this has apparently led Mr. Gill to think that the Post Office has not adopted this form of working. As a matter of fact, it is 4 years since the first 3-channel system was brought into use on Post Office aerial lines. An interesting recent development is the use of two 3-channel systems on the same aerial route between Bristol and Plymouth, a distance of approximately 120 miles. The systems operate on the single side-band suppressed-

carrier principle, using frequencies from 6·3 to 28·5 kc. The lower side-bands are used for transmitting in one direction, and the upper side-bands in the other. The upper frequencies are staggered in order to reduce any tendency to cross-talk. The effective audio-frequency range of the carrier channels is from 250 to 2 600 cycles. The physical audio-frequency circuit has a range up to 5 500 cycles, and can therefore be used as an emergency music circuit if required. The systems are operating excellently, and there is no interference with each other or with the audio circuits on the same wires. One of the aerial wires recently broke down and completely stopped the physical circuit but the carriers continued to work, although at reduced efficiency. There will soon be twenty 3-channel systems in operation.

A number of single-channel systems of the type developed by the Research Department of the Post Office are in use, and an interesting point is that between Glasgow and Inverary—a distance of approximately 50 miles—4 of these single-channel systems are operated on the same aerial route, and moreover it has been possible to add 2 second-channel systems on this route. The second channels have a carrier frequency of 13 000 cycles.

With regard to Fig. 1, which indicates in outline the trunk cable system of the Post Office, it may be of interest to state that 85 per cent of the trunk mileage consists of cable, and that of the 12 million miles of Post Office wire over 91 per cent is in the form of underground cable.

Within the past month, 42 single-channel carrier circuits in cable have been provided between London and Edinburgh, Glasgow, Newcastle, Leeds, and other large cities in the North, and are proving satisfactory. These circuits and the audio circuits in connection therewith are working on cable pairs previously used for telegraphs. They were freed by the adoption of voice-frequency telegraphs on telephone pairs, and were then reconditioned for the above purpose. Arrangements are now in hand for providing 19 single-channel carrier circuits on the 19-quad submarine cable laid between England and France in 1933.

As an indication of the development of long-distance working in Great Britain, it may be mentioned that whereas in 1925 there were only 6 circuits between London and Scotland there are now 90. The 6 circuits referred to utilized aerial conductors each weighing 800 lb. per mile, the diameter being approximately $\frac{1}{4}$ in. The attenuation in the trunk link was 16 decibels. The conductors now used weigh 25 lb. per mile, and the attenuation is zero.

The scheme for 2-wire working described in the paper shows great ingenuity, and it is about to be subjected to an extensive field trial. The Post Office is endeavouring to provide a trunk system free from risk of serious interruption due to the breakdown of cables. With this end in view it is building up a system of alternative routes so that if, for example, there is a direct route between points A and D, it shall also be possible to reach point D from point A via B or C or via both B and C, and that the quality of the transmission shall be the same whatever the routing. It is possible to do this with the present system of 4-wire zero circuits even

when the circuits are extended for many links beyond D. It will be necessary to ascertain by practical trial whether the 2-wire circuits will fit into these schemes, but even if they do not there is no doubt that there will be a field of use for circuits of this type.

Mr. T. S. Skillman: With reference to the author's request for suggestions on the terminology for non-linear interference, the term "interference due to modulation products" appears to have advantages in view of the wide use of the term "modulation products" in other technical papers. There seems to be no equally widely-accepted expression embracing all the products arising from non-linear characteristics. Thus, if we apply currents of two frequencies p and q to a non-linear system, we obtain "modulation products" of frequencies $mp \pm nq$, where m and n may have any integral value 0, 1, 2, etc. Audio-to-carrier interference, arising from two frequencies p and q in the audio-frequency band, is due partly to the products mp and nq and partly to the products $(mp + nq)$, where these lie in the carrier range; similarly, carrier-to-audio interference, where the original frequencies p and q both lie in the carrier range, is due to the products $(mp - nq)$. The third case of cross-modulation is due to the products $(mp - nq)$, but in this case p lies in the audio-frequency range and q lies in the carrier-frequency range. Now, a very large amount of work has already been done in the calculation of the magnitudes of these modulation products for comparatively simple non-linear systems such as triode amplifiers, pentode amplifiers, straight-line and square-law rectifiers, and iron circuits. This work will have an extended field of use as soon as the link between modulation products and cross-talk as measured by observers is completed.

The investigation of cross-talk described in the paper seems to lead towards such a correlation which may be of great value. On an overall system pure frequency measurements are probably misleading, on account of rapid relative phase-change of different products with frequency; but it seems possible in many cases to make such measurements on components, and then to sum them on a random or a maximum basis, depending upon the number of components in series in the system.

The practical outcome would then be that we should be able to measure or calculate levels of modulation products in components, using for this only two frequencies at a time, and from the results we could apportion the distortion effects between the various components in the most economical manner, and be reasonably sure that the overall cross-talk would stay within permissible limits. This is in effect what we have to do in order to decide at all when a component is good enough even to be tried in a carrier system; but, in the absence of the correlation data, there has to be a good deal of guessing in formulating limits. May we therefore know the opinion of the author as to the possibility of such a correlation between cross-talk and the production of modulation products in (a) systems where non-linearity is primarily existent in only one component, and (b) systems where more than one stage of non-linear distortion occurs?

If the author has a curve for a case similar to case (b) in Fig. 11 but in which the loading-coil constant

is very much smaller, so that the effect is predominantly due to the amplifier, and if the amplifier is the same for cases (a) and (b) respectively, it would be interesting to attempt to correlate the two curves with data on the modulation products of the amplifier.

Is it possible that for many purposes further simplification might be proposed, and data on the production of harmonics alone be used as an indication of the presence of other demodulation products? If this were done, simple harmonic measurements might be formulated, the limits being different for each type of non-linear system (valves, rectifiers, etc.), such that overall conditions could be met without too-onerous manufacturing requirements. Such results would be of very great service to the industry.

In view of the author's remarks to the effect that intelligible cross-talk of an attenuation of 75 db is detectable in the limiting case of a quiet room, does he regard secrecy as of fundamental importance in cross-talk limits, and is it right to consider that a limit of 55 db is a proper limit only when the cross-talk is unintelligible? It is not clear how it is possible to reconcile this with the statement as regards signal/noise ratio in line 12 from the bottom of col. 2 on page 609.

In view of the increasing tendency towards the use of multi-electrode valves, which produce less second harmonic and more third harmonic, it would be very interesting to know what change in third harmonic is obtained as a result of the use of a dry rectifier to neutralize the second harmonic.

The singing point obtainable by reasonably cheap balancing networks against filters is generally rather low. We may safely assume that the author's solution is not an expensive one, and an indication of the construction used and the singing point obtainable would be valuable.

Mr. G. J. S. Little: As generally understood, the function of an echo-suppressor in a 4-wire circuit is to prevent electrical echoes from interfering with the talking and listening subscribers. The author refers also to the action of the echo-suppressor in a zero-loss 4-wire circuit in preventing a howl from building up to troublesome dimensions during any short period when the ends of the circuit may be open. In a zero circuit the echo-suppressor performs another function which has not been mentioned.

Echo in a long 4-wire circuit is a manifestation of circulating currents which are also present when the time of transmission of a circuit is too short for their perception as echo. In extreme cases, circulating currents can cause appreciable distortion.

When two subscribers who have short exchange lines are connected directly to the ends of a 4-wire zero circuit the margin of stability is small, the sum of the singing points at the two ends being about 10 db. This applies to frequencies in the middle of the speech range; the figure may fall to 5 db at 200 or 2 000 cycles. In such a case I find, by calculation, that the circulating currents superimposed on the direct speech currents cause oscillations in the overall frequency/response curve of the circuit to the extent of 5 db, increasing to 11 db at 200 or 2 000 cycles. These oscillations are likely to take place every few hundred cycles, as the

total phase-shift around the circuit and the phase-changes in the amplifiers are involved. If a variation of 2 db in the overall equivalent is assumed on account of variation in repeater gains, etc., in an extreme case the oscillations in the frequency/response curve will correspond to limits of 7 and 15 db.

Although the cases in which such extreme distortion can occur are rare, the possibility is sufficiently serious to warrant the provision of echo-suppressors on short zero circuits. Echo-suppressors are in fact fitted on all zero circuits in this country, and will no doubt also be required on circuits provided by the newer types of carrier systems which have been mentioned during the discussion, even though their speed of transmission will be high.

Mr. B. H. McCurdy: It seems to me that more mention should be made of the open-wire carrier system, not only from the standpoint of international telephony but also for purely national telephony.

There is still a large number of countries in which the distances and the demand for service between points are such that a cable network cannot be foreseen for some time. Such has been my experience with the Rumanian network, where the distribution outside the cities is entirely on the basis of open-wire lines. The application of the carrier system, both single- and 3-channel, to the interconnection of the toll centres has proved of enormous advantage. Whereas 5 years ago long-distance telephony in Rumania was confined for the most part to distances of from 60 km to 100 km, to-day practically any subscriber within the country can talk to any other subscriber and can reach the international switching centre over connections meeting C.C.I.F. limits. Practically all circuit additions made since 1930 (which incidentally amount to some 60 per cent of the total circuit length in service in 1930) have been obtained by the use of carrier channels superimposed on the existing open-wire lines (see Fig. A). This arrangement has been advantageous not only from the standpoint of economy—an important factor—but also from the standpoint of getting circuits of good quality. What actually was done was to select seven regional centres and to interconnect these by open-wire carrier systems operating at 6 db, but lined up to work at zero attenuation when switched. This is a somewhat different practice from that which the author has outlined.

I am not happy about the concept of a zero circuit as a general design standard. One may take a given circuit of reasonable length, line it up to zero attenuation, place at each end a subscriber with a limiting loop (from the stability standpoint), and obtain a conversation which is satisfactory from a commercial point of view. A number of factors, however, have led me not to regard such a circuit as a "zero" circuit when considering it as a part of the general long-distance network. In the first place, we must consider the variations in the equivalent of such circuits with time which result from such factors as variation in gain of the repeaters. In the second place, there is the question of echoes. As the author has shown, these can, for circuits of moderate length, be eliminated or at least greatly reduced by the echo-suppressor. On very long circuits echoes do, however, even when echo-suppressors are used, constitute a factor limiting the minimum equivalent at
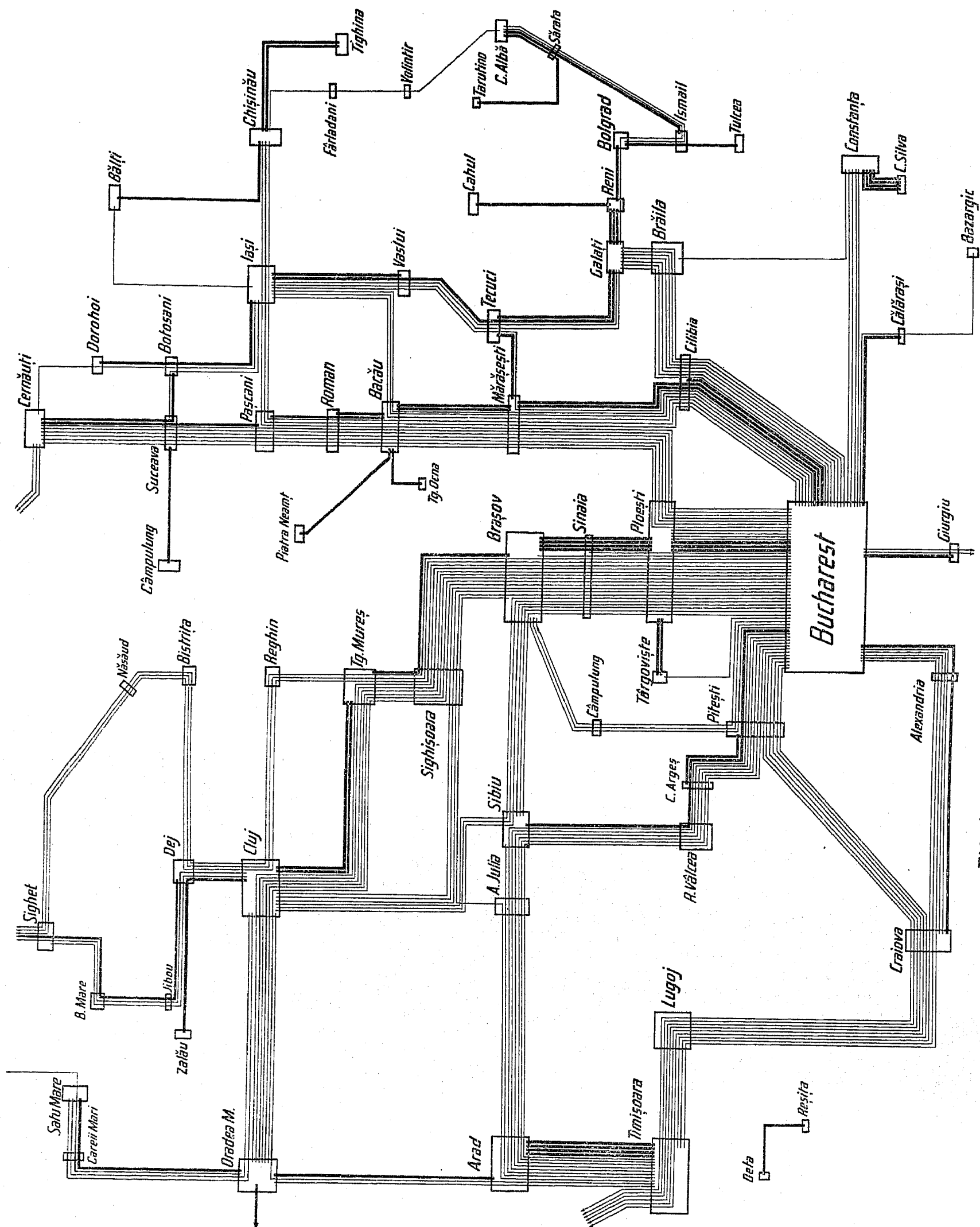
Fig. A.—Use made in Rumania of carrier telephone circuits.

The chart indicates method employed for adding circuits on existing leads during period 1931–33.

— Carrier channels.

— New copper circuits.

which a circuit can be worked. Then there is the question of " near singing." With the " zero " circuit and with very short loops at each end, we may not obtain actual singing, but we do get a condition in which the quality of the conversation deteriorates owing to " near singing," and we have found it necessary in order to eliminate this deterioration in quality to keep the margin between the singing condition and the actual working condition to at least 7 db, and, if possible, 10 db. Finally there is the question of cross-talk. With any group of circuits within the same cable or on the same lead the possibility of overhearing conversation from another circuit in the same group increases as the net transmission loss of the circuits in the group is decreased. For a given cross-talk limit there is, therefore, for a given type of circuit a minimum allowable loss from a cross-talk standpoint.

These factors have led us to consider the possible equivalent, to which the circuit may be reduced, to be not zero but something greater than zero. First, there is the absolute limit to which we could conceivably reduce the equivalent, the actual value being roughly a function of the length of the circuit. Secondly, there is the additional margin which we must provide in the circuit owing to the unavoidable variations in gain which may occur throughout the day. For that reason, although we do have circuits lined up at zero between our regional centres, they are not used as such, except as part of a transit connection.

The advantages of circuits lined up to zero loss, especially when we come to our inter-regional circuits, cannot be questioned; there is the facility which the author has mentioned of building up auxiliary routes between large zone centres. On the other hand, unless such circuits are padded out for their terminal condition, there is great danger of running into these difficulties of " near singing," echo, and cross-talk, to which I have referred.

There is also the question of the reaction on the subscriber. Just what that reaction will be depends somewhat upon the method of designing and laying out the smaller areas. If, for instance, the area dependent on a major switching centre is laid out to meet, say, a 28-db to 30-db standard, we may have a rather unfortunate contrast in transmission and one which may react unfavourably on the telephone company. Thus a subscriber in the centre of a city who makes a toll call over a zero circuit to a similar subscriber at, say, a point 600 km or 700 km away, will then obtain a perfect conversation at almost zero level. On the other hand, if the same subscriber calls up a limiting subscriber in his own 20-km or 30-km tributary area he may get a connection of some 15–22 db. The reaction will be not "How good the 700-km connection is " but rather " How poor this local connection is," even though the latter is quite satisfactory. It is this question of contrast which has worried us, and we have had a good deal of comment on it even where our circuits, instead of being zero, have been of 6 db. This is another reason why we have found it advantageous to pad out, and not work at zero attenuation for terminal calls. In fact we have even considered padding-out to 9 db.

Mr. A. J. Aldridge: The author and several of the speakers have referred to the negative feed-back amplifier. Negative feed-back is, of course, quite well known, but several new and extremely useful properties of it seem to have been discovered. For example, I understand that it very nearly eliminates amplification variations due to battery supplies, and also eliminates harmonics. Further, as is mentioned in the paper, cross-modulation does not seem to worry it.

If it is possible to employ a single amplifier per section of the line to deal with all the carrier channels in this section, without intermodulation, the economics of the system obviously become far more favourable; in fact, the latest multi-channel system appears to depend entirely on the use of such a repeater, and I think that if the author could give us some physical explanation of the behaviour and the performance of this type of amplifier it would be very useful.

Mr. K. E. Latimer: I should first like to refer to the Decker or frequency-changing method of stabilizing a telephone circuit. I do not propose to discuss whether it is effective or not, but merely to point out that it is very easily applied to a carrier system. All that is necessary is to adjust slightly the frequency of the oscillator either in one of the modulators or in one of the demodulators, in which case each time an echo goes round the path it will be stepped up or down in frequency. I should like to suggest that perhaps use has been made of this system inadvertently by inaccurate adjustment of the modulators or demodulators, and this may account for some of the reputed stability of carrier circuits. I do not suggest that the improvement obtained is very great, because from experience of such a system I find that if the gain is increased only a little above the point at which one would expect the circuit to sing, a slight howl, varying both in amplitude and in frequency periodically with time, certainly occurs.

Secondly, with regard to the 4-wire terminating sets which have high-resistance windings, I should like to suggest that high resistances R [where $\sqrt{(Rr)} = 600$, r being the resistance of the winding] placed across line and network terminals of such sets will form, together with the resistance of the winding, attenuators which will increase the loss from 2-wire to 4-wire in the terminating set up to $(3 + x)$ db, where x has the same significance as in the paper. The loss from 4-wire to 4-wire will be exactly double, namely $(6 + 2x)$ db. Therefore, by raising the gain of the repeaters it should be possible to obtain exactly the same working conditions as with the ideal 4-wire terminating set. Further, since this expedient will also bring the input impedance of the circuit nearer to 600 ohms, it will also improve the switching conditions. Again, by the same process one may dispose of the leakage inductance. If one shunts the line or network with a small capacitance, that, together with a leakage inductance, forms a half-section of a low-pass filter having, say, 600 ohms impedance, and again the desired result is obtained.

With regard to the use of valve echo-suppressors on 2-wire lines, I should like to point out that other types of echo-suppressors are in fact also capable of being so used. I have definite knowledge of a case in which a grid-jamming type of echo-suppressor was applied successfully to a 2-wire cord-circuit repeater.

The amounts of "clipping" associated respectively with the relay and the Ryall types of stabilizers are not greatly different. I have managed to reduce the time taken by a relay-type stabilizer in changing direction—that is to say, in passing from north to south over to south to north—down to 4 milliseconds, whereas I understand the Ryall stabilizer takes 2 milliseconds to become operative from the neutral position, and therefore presumably 4 milliseconds to change direction. In view of the fact that it is difficult to distinguish a clipping of even so much as 20 milliseconds, I suggest that there is no great practical difference between the two. Incidentally, the same facility, that of break-in, is obtainable also with the relay type of stabilizer.

Another stabilizer of the relay type has recently been successfully applied to the Italy–Sardinia submarine telephone cable, this time on a 2-wire carrier system.

I am interested in the author's remarks on transient phenomena. He mentions four undesirable effects so produced, to which I would add a fifth which may not have been present in his tests. It has been noticed by several observers that the transient increases appreciably the length of an echo, so much so that if one talks upon a 2-wire circuit which is badly equalized, and on a 4-wire circuit having the same length and the same loading, but equalized, one may judge the echo on the 4-wire system to be the worse, on account of this effect.

I am interested in the author's statement that a reduction of apparatus cut-off from 2 700 down to 2 400 cycles made no difference to the transient effects. In 1927 I made some tests on transients in which it was found that reducing the apparatus cut-off from 2 400 to 1 800 cycles did reduce the noise effect of the transients. The articulation did not change appreciably, however, because the distortion due to lower cut-off was cancelled by the reduction of transients. (These results were subsequently confirmed by Mr. Rendall.*) This raises two points. Firstly, the C.C.I. definition† seems to require amendment, in that a representative frequency other than the maximum frequency of the band should be specified at which transients should be calculated. Secondly, the inadequacy of articulation tests in work of this kind is emphasized, as already implied by the author, in that the relative importance of noise and distortion may not be the same for articulation tests as under service conditions.

Dr. L. E. C. Hughes (*communicated*): The author asks for more suitable terms for intermodulation distortion; I have found the word "blur," corresponding to the German *klirr*, a useful description. There are various kinds of blur, so that the term must be made specific. We have, for example, audio blur, arising from any non-linearity; audio—carrier blur due to modulation up; carrier—audio blur, due to modulation down (or demodulation); Class-A blur, which differs from push-pull blur or Class-B blur in amplifiers, in that a given measure of it has different implications as far as the ear is concerned, because of the different distribution of alien tones. In acoustics we have a further kind of blur, called reverberation blur. For measurement of

blur, one may take the Kellogg blur factor, which depends on amplitudes of the alien tones as compared with amplitudes of the desired tones; or the Küpfmüller blur factor, which depends on powers of the alien tones as compared with powers of the desired tones. A reasonable alternative is blur level, which gives the decibel difference of alien power and desired power, at any part of a circuit. There does not appear to be any agreed procedure for measuring blur, except applying a constant frequency and lumping the harmonics as second order. Some weighting due to their increasing aural importance with frequency should be agreed on; Class-B blur is much more annoying to the ear than an equal measure of Class-A blur, because of prominent high harmonics.

Mr. A. C. Timmis (*in reply*): It must be admitted that the term "long-distance telephony" is somewhat vague. Perhaps "telephone trunk line transmission" would more accurately describe the subject of the paper.

Although the longest trunk line in this country is unlikely to exceed 600 miles, the Post Office is by no means unconcerned with distances which would be regarded as long in America or on the Continent of Europe. As a member of the C.C.I.F.—the co-ordinating authority for international telephony—the Post Office takes a full share in the study of long-line problems, and the development of new methods. It may be recalled that, in his inaugural address,* Mr. Gill was the first to suggest the formation of an authority such as the C.C.I.F. Now the Continent of Europe is covered by a telephone network comparable with the Bell System in America. This change might have been possible without the thermionic valve but it would certainly not have been economic, and in this sense the recent growth of international telephony may be said to be due to the advent of the thermionic valve.

The mains-operated carrier system is not provided with standby batteries because it is not intended to form the only trunk connection between two exchanges, and the addition of batteries would spoil the compactness and portability of the system. For a 3-channel system, standby batteries would usually be justified.

Col. Lee and several other speakers refer to the negative feed-back amplifier. This invention has made practicable the transmission of a large number of carrier channels over a line containing amplifiers, and has thereby revolutionized the art of carrier telephony. The principle of the negative feed-back amplifier is fairly simple, but it is not too much to say that the advantages derived from it are astonishing. Taking a numerical example, in a typical amplifier the gain (expressed as a current ratio) of the high-gain amplifier itself may be 300, and the feedback $\frac{1}{20}$ of the output. Then the net gain of the arrangement will be roughly 20, and the amplifier will have the following advantages over an ordinary amplifier having a gain of 20: (1) Any change of gain due to such causes as variation in valves or supply voltages is reduced approximately in the ratio 20/300 by the stabilizing effect of the feed-back. (2) Noise currents arising inside the amplifier are reduced in the same ratio. (3) Harmonics due to non-linearity in the amplifier are reduced, and the linearity of the amplifier is improved, in the same ratio. (4) Phase-shift is also reduced.

* *Electrical Communication*, 1930, vol. 8, p. 320.
† C.C.I. *Livre Blanc* (Report of Budapest Meeting, 1934), vol. 3, p. 25.

* *Journal I.E.E.* 1923, vol. 61, p. 1.

For telephony, advantage (3) is the most valuable, as it means that a large number of carrier channels may be worked through the amplifier without non-linearity interference. These and other properties of the negative feed-back system are explained qualitatively, with the aid of a mechanical analogy, in an article which has recently been published elsewhere.*

Voice-frequency telegraph systems of the type mentioned by Mr. Montgomery are now used for all the main telegraph connections of the country, and it is important that any 4-wire telephone trunk, whether it is an audio or a carrier channel, should be available as the "line" for a voice-frequency telegraph system without special adjustment; otherwise full advantage could not be taken of the flexibility provided by the main trunk system with its ample choice of alternative routes. Hence arrangements have been made to keep the carrier frequencies of the cable systems described within ± 1 cycle of their normal value. Actually, the present voice-frequency

international link, should degrade the frequency response less.

The various types of linear and non-linear disturbance have been set out in tabular form (see Table), as suggested.

I am grateful to Dr. Hughes and Mr. Skillman for suggesting, respectively, "blur" and "interference due to modulation products" to describe what I have called "non-linearity interference." Neither term succeeds in being at the same time brief and descriptive, however.

As regards the chance of an aerial-line carrier circuit singing (at carrier frequency), Mr. van Hasselt may rest assured that the possibility is very remote. To avoid any risk of "near singing" distortion these circuits are usually adjusted to an equivalent of 3 db. Echo-suppressors would remove the risk (as Mr. Little explains), but it is usually neither convenient nor economical to fit suppressors on these carrier circuits.

The variation of 2 or 3 db in line attenuation mentioned in the paper should be regarded as an extreme.

Table
CROSS-TALK AND SIMILAR TYPES OF INTERFERENCE.

Usual term	Description	Unit
Cross-talk	Overhearing of speech from one circuit to another	Millionths of disturbing voltage, or same ratio in decibels
Cross-talk attenuation	Cross-talk ratio expressed in decibels. Usually "cross-talk," for brevity	—
Babble	Speech from a number of circuits overheard as confused murmur	Voltage of equivalent steady tone, or level in decibels below 1 milliwatt
Cross-modulation. Non-linear cross-talk. Inter-modulation. Non-linearity interference.	Unintelligible noise, or "blur" having rhythm of speech from which it is derived. Due to two circuits (speech bands) working through common apparatus, such as amplifiers, of which the response is not linear	Voltage of equivalent steady tone, or level in decibels below speech producing the interference, as judged by aural comparison

telegraph systems could tolerate a greater difference of frequency between the ends of a carrier channel, but it is an easy matter to maintain the frequencies within such a tolerance, by keeping the tuned circuits of the master oscillator in temperature-controlled boxes. From the telegraph point of view it is an advantage to know that a carrier speech channel introduces no variation in frequency over and above the slight variations due to fluctuations in the speed of the machines which generate the telegraph carrier frequencies.

As Mr. Cohen observes, there is a natural temptation to overlook the economic possibilities of the existing network when considering attractive carrier schemes of the future. In this connection the curves of Fig. 3 will prove interesting. They show the very satisfactory frequency response which can be obtained for 2-wire circuits on modern cables loaded for audio frequencies. It will be seen that all the curves are well below the C.C.I. limits, as they should be. An international trunk call often involves one international link and two national trunks, and economic conditions demand that the national trunks, being generally shorter than the

It is, however, consistent with the variation of 1·2 db on a total of 12 db, for the maximum attenuation which the Post Office mains-operated system covers is 26 db. With good valves the change due to ordinary mains voltage variations is negligible. As regards the limitation due to instability or cross-talk on 2-wire circuits, the statement quoted by Mr. Van Hasselt is certainly true for British practice. In a particular case—the London–Liverpool (1930) cable—the measured cross-talk between two 2-wire circuits in the same quad (200 miles) was 70 db. The effect of babble would evidently be quite negligible.

The chief application of stabilizers will probably be to the older cables. Some 4-wire circuits will be converted to 2-wire, and some 2-wire circuits now working at overall equivalents well above zero will be made into zero circuits, and thus fit in with the general system of zone-to-zone trunks.

The cross-talk measurements on French aerial lines seem to agree with results obtained in this country and in Sweden. In both the latter cases the continuously twisted square is used, so that the effect of any consistent departure from the square formation—such as

* A. C. TIMMIS: *Post Office Electrical Engineers' Journal*, 1936, vol. 29, p. 71.

9 in. horizontal and 12 in. vertical spacing—is eliminated. In France, however, quarter twists are inserted at intervals and thus irregularity of formation is less likely to cancel out. Even in the case of continuous twist it is found that cross-talk between diagonal pairs is worse than between pairs in adjacent squares. This is illustrated in Fig. B, which gives some results on a 100-mile line of the old, twisted square, formation.

The term " signal/noise ratio " is used as a matter of convenience when dealing with the design of circuits whose equivalent is to be zero, or a very few decibels. It is agreed that " cross-talk " or " cross-talk attenuation " is more strictly applicable to the case of intelligible speech overheard at the end of a circuit, but, for noise or babble, the signal/noise ratio is applicable and it avoids the necessity of stating the nominal level at the point of measurement.
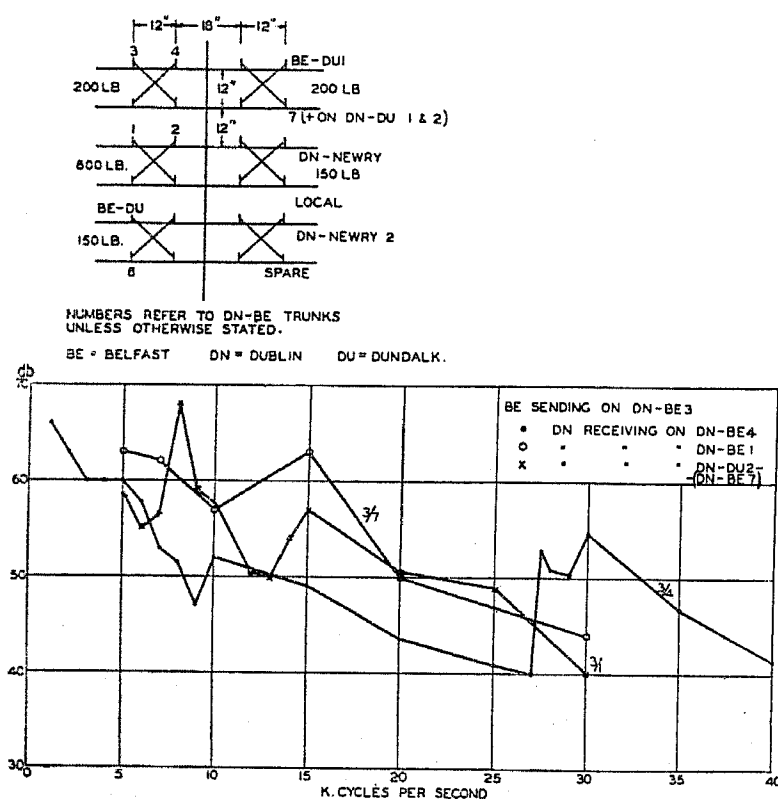
Fig. B.—Carrier-frequency cross-talk on aerial line (continuous twist).

The 3-channel carrier system referred to by Captain Hines is the American system used on long aerial lines in many parts of the world. In this country, however, it is not generally economical, and the installations mentioned are in the nature of temporary measures to meet the increased traffic due to the recent reduction of trunk charges.

The principal factor which decides whether 2-wire zero circuits will fit into the general scheme of zone-to-zone trunks is stability. Provided, therefore, that the 2-wire circuits are as stable as the old 4-wire circuits (which they can be), they may be regarded as interchangeable with the latter.

In reply to Mr. Skillman, we have found it possible to predict the amount of non-linearity interference due to speech in one component, such as a repeater, by measuring the interference produced by two tones having the same total r.m.s. value as the speech after passing through the limiter. If there are several components the effects may be added on a random (power) basis. Using the simpler

method of one tone, the harmonic content for a particular component can be correlated with the result of speech tests, by experience. Such correlations are useful for design purposes. As mentioned in reply to Mr. Van Hasselt, I agree that the absolute level of intelligible cross-talk is what determines how much cross-talk attenuation we can tolerate. If, for example, the overall equivalent of two circuits is 5 db, and the signal/noise ratio (cross-talk) is 55 db, the cross-talk level is — 60 db. With a reasonable minimum of line and room noise, speech at this level is practically unintelligible. When the " cross-talk " consists of noise which is unintelligible at any level a signal/noise ratio of, say, 50 db can be tolerated, as the noise merely disturbs the listener; whereas overheard speech may interest him and embarrass the telephone administration.

The metal-rectifier compensator does introduce some 3rd harmonic, but in practice this is negligible compared with the 3rd harmonic due to the loading coils. In the carrier-to-audio direction the interference is mainly rectification of side-band due to single curvature of the valve characteristic, which produces 2nd harmonics. Third harmonics produced by the double curvature of loading-coil characteristics. would cause some demodulation of the side-band, indirectly, but only as a second-order effect.

The final paragraph of Mr. Skillman's contribution presumably applies to the balancing networks used in the construction of high-grade 2-wire circuits. I have now included (see Fig. 3) in the paper as revised for the *Journal* a typical impedance/frequency curve for a repeater section on the Liverpool–Glasgow cable, from which it will be seen that the smoothness of the impedance curve enabled a very satisfactory singing-point to be obtained against a balancing network of the usual type containing two resistances, one inductance, and three condensers.

I agree with Mr. Little that it is advisable to fit echo-suppressors on all zero circuits in order to remove any risk of incipient oscillations.

Mr. McCurdy's information as regards long-distance telephony in Rumania emphasizes the practical utility and economy of the aerial-line carrier systems, especially where distances are long. As regards the zero circuits, I do not suggest that they are suitable for general use outside this country. For instance, when the main trunks of a system are provided by means of 3-channel aerial-line carrier, the cross-talk difficulties may easily make it necessary to limit the minimum overall equivalent to 7 or 8 db. From the point of view of stability I think the limit could generally be much lower.

The argument that we must not reduce the attenuation of a trunk line too much, because of invidious comparison with a local call, does not seem a very strong one. If complaints did arise as suggested by Mr. McCurdy, telephone users could no doubt be pacified by judicious publicity.

Mr. Latimer's suggestion that carrier circuits may have acquired some of their reputation for stability by fortuitous frequency variations is very interesting, but I do not think it applies to recent carrier systems. These are as stable as ordinary 4-wire circuits, no more and no less.

The method of neutralizing the effect on stability of the differential transformer resistance is extremely neat

and certainly more economical than fitting new transformers. As regards 2-wire echo-suppressors, I agree that the valve type can be made to work on a 2-wire repeater; but unless special precautions are taken to prevent false operation, e.g. by means of interlocking and limiting devices, the suppressor will only work under favourable conditions. The metal-rectifier suppressor lends itself very conveniently to the use of a differential interlocking arrangement.

The essential difference between the relay type of stabilizer and the metal-rectifier type is in the "break-in" facility, but only a limited amount of "break-in" can be obtained unless means are provided to prevent echoes themselves from "breaking-in." Adequate break-in facility, such as is required on a stablized repeater for general use under all conditions on trunk lines, is obtained in the Ryall stabilizer because the echo is prevented from breaking in by a special circuit arrangement whilst ample break-in facility for speech is retained, with sufficient hangover time to avoid a jerky effect. In general, metal rectifiers have the advantage of relays in economy and reliability, if not in speed of operation.

As regards the effect of transients, I agree with Mr. Latimer that the transient noises produced by speech frequencies over 2 400 cycles are negligible compared with those due to frequencies in the range 1 800-2 400 cycles, which are fairly strong in speech, from a carbon transmitter at any rate. In the tests which I described there was no echo effect. The full length of line available was used, with one-way transmission, to obtain a reasonably audible transient. In practice it is more usual to hear the transient "tweet" at the end of an echo than in received speech. In the former case, of course, the time is twice as long. The C.C.I. transient limits refer to an upper frequency of 2 600 cycles, by implication, since that frequency must be transmitted with a loss of not more than 9 db compared with the frequency of 800 cycles, but no upper frequency is specified.

Since the advent of multi-channel carrier systems, however, the importance of phase distortion (and compensation) has decreased considerably, at least in the field of telephony. Probably the long, heavily-loaded circuits which alone require phase compensation are now uneconomic compared with multi-channel carrier systems.

NORTH MIDLAND CENTRE, AT LEEDS, 4TH FEBRUARY, 1936

Mr. C. J. Jones: I should like to emphasize the point that quite a large amount of power is required at large repeater stations. At Fenny Stratford repeater station the power plant consists of two 80-h.p. semi-Diesel oil engines, with two 32-kW d.c. generators for charging the 10 000-ampere-hour filament batteries, which supply the filament current for 2 000 valves.

The London–Birmingham–Liverpool cable mentioned by the author replaced a cable (London–Birmingham No. 3) laid in 1916, which at that time was the longest loaded cable in Europe. The old cable consisted of 300-, 200-, 150-, and 100-lb. conductors, and its capacity was 52 pairs. The new cable has 4 pairs of 40-lb. metallic screened conductors and 352 pairs of 25-lb. conductors. The weight per mile for the old cable was 15 200 lb. and for the new cable is 17 600 lb.; therefore an increase of 300 pairs has been obtained for an increase of 2 400 lb. of copper per mile.

It is interesting to recall that the first telephonic repeater was used at Leeds in a London–Glasgow circuit in 1914. I refer to the S. G. Brown relay, associated with a jumping switch which controlled the direction of amplification.

Prof. E. L. E. Wheatcroft: I should like to ask the author a question about the voice-controlled relays. In the original arrangements for transatlantic telephony, voice-controlled relays were installed to prevent singing, and it was necessary to arrange for a delay circuit in order to allow the relay time to act before the voice came through. I gather that such an arrangement is not used in the long-distance telephony of to-day. Is this development a result of progress, or is it a peculiarity of the land-line as distinct from the radio channel?

Mr. R. M. Longman: I should like to ask the author whether he can give some details of the submarine cable recently laid between Australia and Tasmania, which I understand represents the very latest achievement in design and by which a single pair of wires can be utilized for many circuits.

Mr. D. W. Cherry: Some of the circuit arrangements referred to are very interesting and ingenious, and I should like to discuss the relative advantages of the various systems as seen from the maintenance engineer's point of view. To meet modern requirements the majority of repeatered circuits must be of high quality and zero loss, so that, if 2-wire working is to be employed, stabilizers would appear to be essential. The operation of this apparatus is undoubtedly somewhat complicated, and it seems probable that some difficulty might be experienced in the field in setting up a large number of these devices at short notice—a requirement that is by no means uncommon in these days of rapid development. In the event of a fault developing on a stabilizer while in service, the maintenance staff would undoubtedly have difficulty in tracing the trouble; experience with simpler forms of voice-operated devices leads us to this conclusion.

In the past it has been necessary to calculate and construct a different balancing network for each 2-wire circuit in the same cable. This, of course, is a very laborious business and it seems probable that, even with modern cables, this process will still be necessary in order to obtain the highest grade of circuit.

With regard to carrier working on 2-wire audio-frequency circuits, this would appear to have a somewhat limited application so far as the existing main cable network is concerned. With the lighter loading, which must be used in order that the carrier band shall be transmitted, the attenuation between repeater stations on the audio circuit will in general be rather high for satisfactory 2-wire working.

The disadvantages of 2-wire circuits would therefore seem to be: (a) the time taken to set up the circuits and bring them into use; (b) possible maintenance difficulties owing to the stabilizing equipment; (c) reduced intelligibility due to echo.

The 4-wire carrier system, however, would appear to meet requirements both with regard to economy of line plant, ease of setting up, and maintenance. Higher-grade circuits with a better frequency response, freedom from echo, and improved overall attenuation, can be obtained. In addition, the more complicated apparatus is fitted at the main terminal stations where larger and more experienced staffs are employed.

Although no trouble due to phase distortion has been experienced on telephone circuits in this country, it may be of interest to point out that difficulties have arisen with certain types of facsimile transmission apparatus owing to transient effects. In these cases correcting networks have had to be inserted in the lines used.

Perhaps the author's remarks with regard to transients could be amplified to cover the case of single side-band carrier-working on loaded cables. In this case, it will be seen that it is the transmission of the lower speech frequencies of the carrier channel which is delayed. It is usual on a simple 4-wire audio circuit to employ only about 75 per cent of the theoretical frequency-band width; even then the transient effect is noticeable. In one case quoted, the theoretical cut-off is 6 600 cycles, hence the highest frequency normally transmitted would be 4 950. The carrier frequency employed, however, is 5 800, so that a considerable portion of the carrier channel is transmitted in that part of the frequency spectrum which is appreciably affected by phase distortion. In practice the reduction in intelligibility may not be serious, but the point would appear to be worthy of consideration.

Mr. A. C. Timmis (*in reply*): Mr. Jones mentions what was probably the first workable voice-operated switch—used in conjunction with the Brown relay. This relay was really a microphone amplifier, and gave an amplification (at middle frequencies) approaching that of a modern 2-wire repeater. The whole device was never reliable, however.

In reply to Prof. Wheatcroft, voice-operated relays are still used in America for the transatlantic telephone. They were also at one time used here as an alternative to the Post Office valve equipment, but the latter is now used exclusively for all the radio terminals in this country. For land-line stabilizers it would appear that metal-rectifier devices are most suitable on the score of economy and maintenance (see reply to Mr. Latimer, in the London discussion).

Some details of the Australia–Tasmania cable, mentioned by Mr. Longman, were given in the London discussion by Mr. Montgomery. I understand that the preliminary trials have been very successful.

In reply to Mr. Cherry, two distinct types of 2-wire zero circuits are being dealt with. In one case we have modern cables with smooth impedance characteristics which require accurately-made balance networks, but no stabilizers unless a length of 200 miles is greatly exceeded. In the other case, older cables with irregular impedance can only be dealt with by means of the stabilizer, but then no special accuracy of balance is required. Moreover, the newer cables are so uniform in every respect that all the balances may be alike except for a small range of adjustment on one or two components.

As regards the impairment due to echo, I have explained in the paper that any zero-loss circuit requires an echo suppressor, and that the metal-rectifier type of suppressor works equally well on 2-wire and on 4-wire circuits. As regards maintenance difficulties, the first experimental model of the stabilizer worked without any attention for 18 months, after which it was replaced by permanent equipment of the same design.

The frequency/response curves now included in the paper (Fig. 3) for the LV-GW cable show that there is very little to choose between a high-grade 2-wire and a 4-wire trunk in this respect.

In the case of the very lightly loaded high-velocity cable-pairs used for single-channel carrier-working the propagation time is so short that phase distortion in the carrier channel would be negligible, even for a very long line. It is not safe to assume that phase distortion on an audio circuit will be noticed above 75 per cent of the cut-off frequency. It is hardly appreciable until the difference in arrival time between frequencies of 800 and 2 000 cycles per sec. approaches 20 milliseconds.

Phase distortion at the low-frequency end of the speech band such as might occur in exceptional cases with the single-channel carrier system has not been studied experimentally in this country. At present it would appear to be of theoretical interest only.

NORTH-EASTERN CENTRE, AT NEWCASTLE, 10TH FEBRUARY, 1936

Mr. William F. Smith: The provision of line plant is the most costly item in telephone engineering, and economy in this direction is of paramount importance. It would appear, therefore, that intensive research into the problem of making 2-wire trunk circuits satisfactory is justified. It is mentioned in the paper that successful tests have been made at Liverpool with 2-wire circuits working at zero loss. The lack of stability on these circuits presumably arises from the varying impedance of subscribers' lines connected thereto. It is too much to hope that all subscribers' lines could be made standard at some particular impedance value, but it does not appear to be beyond the bounds of possibility to secure some measure of balance so that 2-wire repeatered lines would be practicable. In any case, as the author has mentioned, without very special precautions 2-wire circuits can be worked with a loss of 3–7 db without risk of instability, and reasonably good speech should be possible under such conditions, at any rate for the shorter trunk circuits.

What has determined the limit of three-quarters of the cut-off frequency to which equalization is applied? It would seem that equalization should be carried out to the limit of the frequencies it is required to transmit efficiently over the cable, which presumably will be the value of the " cut-off " frequency.

I am particularly interested in the toll repeater, which employs unrectified alternating current from the supply mains for the directly heated valve filaments. Are any precautions taken to remove the possibility of 50-cycle hum appearing on the speech wave? Equalizing is not attempted on such repeaters; I should be interested to

know at what frequency the gain is fixed and also what is the maximum gain possible with these repeaters. The compact design of this single-stage repeater is a marvel of engineering.

The concentric air-space cable which has recently been introduced would seem to have rather a limited application in this country. The cost of such a cable would probably be more than that of ordinary cables with a similar number of channels of communication, and it would therefore be economical only in those cases where a very large number of channels were justified. Presumably it would not be practicable to divert a number of channels with the same facility as is possible with the ordinary cables. Is it intended eventually to distribute these new-type cables throughout the country or to adopt a main-artery formation with connection, as required, to the present system suitably modified? In the latter case, of course, it would be necessary to reserve the lower-frequency channels for circuits connected to the present cable system. How is it intended to accommodate repeaters on these high-frequency cables? I believe that amplification will be necessary at intervals of about 8 miles owing to the large attenuation at the higher frequencies, and amplifier accommodation becomes a serious problem. It is noted that two cables are being laid side by side for " go " and " return " circuits. There would seem to be no purpose in this except to increase the number of channels; it should be possible to work speech in both directions on the one cable.

The negative feed-back amplifier described is very ingenious but it apparently does not prevent modulation of one frequency by another when passing through the same amplifier.

The instructional film shown by the author this evening is, I think, a very satisfactory aid to the student in assimilating the principles propounded by the lecturer, particularly in the case of such complicated diagrams as arise in telephone engineering. How far is the use of such instructional films being extended?

Mr. Dick Smith: With the reduction in telephone rates and the introduction of demand working on trunk lines, the Post Office—to meet the increased demand for lines—have either had to introduce carrier working or lay more underground cables, and the author sets out in his paper the recent developments in communication by which the present demand for circuits has been met without a very large capital expenditure.

In dealing with aerial circuits, he says that it does not matter if the carrier circuit does howl; but what about the interference to other carrier circuits on the same line, some of which may be working at the same carrier frequency? There would appear to be a danger of overloading the repeater, and cross-modulation would be the result. The cost of erecting wires on a route 30 or more miles in length is said to be greater than the cost of the installation of carrier equipment; is the initial cost or the annual cost the basis of comparison, since maintenance charges will be high owing to more regular tree-cutting, insulator renewals, and regulation of wires?

It would be interesting to know how the stability of 2-wire circuits is affected by the connection of short trunks with their associated amplifiers, since no special equalization is carried out.

It would also be interesting to know whether any difficulties are likely to be experienced in the application of voice-frequency dialling and signalling over trunk lines in the present and future networks of 2-wire and 4-wire circuits with carrier systems. There will no doubt be quite a number of difficulties owing to cross-talk, cross-modulation, etc.

It is now possible to work long 2-wire circuits with a high gain due to the introduction of echo-suppressors and stabilizers at points along the line, but will it be possible to utilize these circuits for carrier working by separating the carrier and audio channels at the repeaters where echo-suppressors and stabilizers are fitted? At present a peak voltage of a certain value is required to operate the stabilizer, whilst in carrier systems any peak voltage is cut down by means of a voltage-limiter.

Mr. J. A. Stanfield: It is the general practice to adjust the output levels on all 4-wire circuits at the transmitting and intermediate repeaters to + 10·0 db above 1 milliwatt. On carrier circuits, so as to eliminate cross-modulation due to non-linearity of the valve, the repeater levels have been reduced to zero. This procedure, whilst very effective, must cause some slight increase in the cross-talk level, and it has been rumoured lately that the level may be increased to + 5·0 db. Can the author say whether this is likely to occur in the near future?

On page 609 the author says* " The most troublesome is usually the 3rd harmonic of the dominant frequency (1 000–1 200 per sec.) in telephone speech." Would it not be better to modify that frequency band slightly to, say, 1 100 to 1 200, owing to the fact that the 3rd harmonics of 1 000 to 1 100 will fall outside the pass range of the receiving filter and be greatly attenuated?

Mr. A. C. Timmis (*in reply*): As regards Mr. W. F. Smith's question, many attempts have been made to standardize subscribers' line impedances, but for various reasons it is impossible to find a better single value than 600 ohms. The range of variation is so wide that it matters very little whether we use 600 ohms or some other value between 400 and 800 ohms.

It is a matter of experience with loaded cables that equalization can be applied without undue difficulty up to three-quarters the cut-off frequency. The equalization of a repeater is nearly always carried out by means of a bluntly-tuned resonance circuit, and generally limited to a difference of 10 db in amplification between 800 and 2 400 cycles.

To deal with a.c. hum arising from the filament circuit of a toll repeater it is necessary to provide a special filter to cut off harmonics of the mains frequency, and condensers are fitted in series with the line transformers to reduce the amplification of frequencies below the speech range.

The gain of these repeaters is constant from about 200 to 10 000 cycles and may be adjusted to 30 db as a maximum.

The coaxial-cable scheme does not lend itself to tapping-off at intermediate points. It will be used as a main telephone artery between large centres, the shorter trunks being provided on multi-channel carrier, or voice-frequency cables. The majority of the repeaters will be accommodated in small lock-up buildings. The ad-

* Corrected later.

vantage of two cables lies mainly in the saving of filters. If both directions were worked in each cable the same number of channels could probably be obtained, but filters would be necessary at each repeater to separate the "goes" and "returns." Each repeater would, in effect, be of the 2-wire type; but duplex balances would be out of the question on account of the high gain required.

The film explaining the operation of the stabilizer is intended for use in the Post Office training school at Dollis Hill, where instruction is being given in the maintenance of stabilizers and other voice-operated devices. For this purpose it may be repeated several times or stopped while special points of difficulty are explained. Instructional films have been used previously, but only to illustrate much simpler operations such as pole-erection.

In reply to Mr. Dick Smith; I have dealt with the instability of aerial-line carrier circuits in replying to the London discussion. We do not use common repeaters with the Post Office aerial-line system, so that the question of overloading does not arise.

As regards economy, the carrier is cheaper than new wires for distances of 30 miles, in both capital and annual cost. The worst condition as regards stability, for a 2-wire trunk, occurs when a very short local line is connected at each end. Unless another trunk is insufficiently stable by itself, under similar conditions, it will improve the stability of the whole connection as compared with a short local line.

The transmission of voice-frequency dialling and other signals over a carrier system is less troublesome as regards non-linearity effects than the transmission of speech, since the peak voltages are much lower. It is possible to work a carrier channel over a line carrying a 2-wire stabilized circuit, but it does not seem economic at present. The application of stabilizers is mainly to lines of irregular impedance too heavily loaded to transmit carrier frequencies. I do not think the peaks of speech which cause non-linearity interference are of sufficient duration, and energy, to be of much value in the operation of a stabilizer, but the point is an interesting one to investigate.

Mr. Stanfield refers to the usual repeater output level of $+ 10$ db. The zero-level output was found to give the best compromise for both audio and carrier circuit. It has no effect on cross-talk if all circuits are given the same adjustment (this depends only on the difference between input and output levels), but increases the disturbance from any other circuits which are adjusted to the normal level. In general, however, such disturbance is negligible compared with carrier-to-carrier cross-talk.

I am obliged to Mr. Stanfield for pointing out a slip as regards the dominant frequency of speech (page 609). This has been corrected for the *Journal*. In telephone speech there are components of comparable magnitude up to 1 500 cycles, the 3rd harmonic of which is heard as 6 000 − 4 500 (= 1 500) cycles in the carrier channel.

MICRO-RAY COMMUNICATION

By W. L. McPHERSON, B.Sc.(Eng.), and E. H. ULLRICH, M.A., Associate Members.

SUMMARY

A short historical review of the evolution of wireless communication is given. The method of generation and modulation of micro-rays around 17 cm with a tube having two grid lead-outs is discussed, and it is argued that the grid itself becomes a transmission line of negative leakance. Some experiments with ebonite lenses and zone plates are described. Paraboloidal mirrors, echelon gratings, and hemispherical mirrors, are discussed.

The micro-ray equipments used on the commercial Lympne-St. Inglevert and the experimental Escalles–St. Margaret's links are described. Propagation measurements on these last two links are detailed and it is shown that, although there is an optical path in each case, severe fading, which is different on different wavelengths, sometimes takes place. This fading is attributed to an interference pattern which varies with atmospheric and tidal changes.

The directivity and gain of paraboloidal mirrors and echelon gratings, as determined by experiment, are given.

In conclusion, future possible uses of micro-rays are sketched.

(1) HISTORICAL

There is a natural tendency in the human mind to think of evolutionary progress as proceeding along a straight line, each step leading directly and logically to its successor. In actual fact the process of evolution can often be more strictly represented as occurring along a helical path, in which successive developments lead back to earlier stages—previously abandoned as unlikely to produce further useful results—whose quickening has had perforce to await evolution in directions to which they originally seemed to have only a remote relation. The science of applied electricity contains many examples of such "indirect" evolution, but without doubt one of the best instances is the recent commercialization of micro-ray systems, for it was with micro-rays that Hertz in 1887 performed those classic experiments which are usually admitted to be the genesis of wireless communication as we know it to-day.

While these experiments by Hertz were confined to a laboratory scale, he succeeded in generating, by means of a spark transmitter, wavelengths as short as 30 cm, and in proving conclusively that the radiation due to such circuits followed the optical laws of reflection, refraction, and propagation, confirming thereby the theoretical work of Clerk Maxwell in the year 1865. The story of his investigations reads almost like a study of light, including as it does reflection from plain sheets of metal, with measurement of the angles of incidence and reflection, reflection from curved metallic mirrors of definite focal length, refraction through prisms of pitch, and studies in transparency and opacity. Owing to lack of sensitivity on the receiving side, these experiments of Hertz bore no immediate fruit although they excited great attention.

Following the invention of the large aerial and of "tuning," the success of medium- and long-wave operation led to total neglect of micro-ray technique until 1919. The theory of the oscillating valve was by that time fairly well developed, and it had been found possible to produce wavelengths as short as 5 metres, using what might be called orthodox systems, but there seemed to be a definite limit to the extent to which the wavelength could be decreased. To Barkhausen and Kurz belongs the credit for having discovered in 1919–1920 a new type of oscillatory circuit with which they generated wavelengths down to about 43 cm. This system of oscillation differs radically from that used in the orthodox longer-wave transmitters in that the grid, instead of the anode, is the power-handling electrode, while the transit time occupied by the electrons in passing from cathode to anode has an important influence on the wavelength obtained; in the orthodox circuits using valves of any normal construction the transit time of the electron stream has no direct effect on the wavelength. From 1919 onwards a considerable amount of work was done in all quarters of the world in connection with the study of micro-rays produced by electronic oscillators, either in the Barkhausen circuit or in other circuits different in form but involving the same basic factors. For a long time, however, no practical results seemed to be forthcoming. It was not until 1929 that any really definite mark of progress can be recorded. In that year Beauvais succeeded in transmitting telegraph signals 37 km on a wavelength of 17 cm.

A big step forward was made in March, 1931, when the first large-scale public demonstration of modern micro-ray working was given by Standard Telephones and Cables, Ltd., and Le Matériel Téléphonique in France, over a duplex radiotelephone link across the English Channel. The terminals of the link were located, one at St. Margaret's Bay, near Dover, and the other at Escalles, near Calais, the distance between the two being approximately 35 km. A wavelength of 18 cm was used, sufficiently short to permit the use of a highly directive radiating system designed almost on optical lines and embodying the use of aperiodic reflecting mirrors instead of the customary tuned reflecting aerials spaced so as to give a directional bias to the radiated field.

The success of this demonstration aroused world-wide

interest, and stimulated a spate of experimental work, some involving communication over considerable ranges. Marconi, for example, made a series of tests in the Mediterranean over distances up to 250 km on the wavelength of 57 cm. On the 11th February, 1933, a permanent link was opened for service between the Vatican City and Castle Gondolfo, near Rome, using a wavelength of 60 cm, covering a distance of 20 km, and providing a private radiotelephone service between the two terminals. This wavelength of 60 cm, it may be noted, is considerably longer than the wavelength of 18 cm used in the 1931 demonstration, and the radiating system is based on orthodox radio practice, resembling an elaboration of the aerial array systems already made familiar by work on the 10–100-metre band. On the 26th January, 1934, a micro-ray link was opened for commercial service between the aerodromes of Lympne in England and St. Inglevert in France, covering a distance of 56 km on a wavelength of 17·4 cm, and providing a duplex service on radiotelephony, teleprinter, or Morse telegraphy, as required. This link uses the shortest wavelength of any commercial station in the world, and is equipped with radiating systems based on optical rather than electrical principles, the main reflector being a paraboloidal mirror instead of a parabolic array as used on the Vatican link, the frequency of which is nearly two octaves lower.

It is a feature of modern civilization that seldom can the credit for inventing a system be attributed to any one man, and that in the majority of cases the development of a system represents the integrated efforts of many individuals working independently. Nevertheless, there are always some whose names can be specially connected with definite steps in the growth of the art. Of these, Hertz, Barkhausen, and Kurz, have already been mentioned; and with them may be coupled Gill and Morell, who studied other possible methods of using triode valves to generate micro-ray frequencies, and also Zacek, Okabe, and Yagi, who during their researches into magnetron effects investigated methods of generating very short wavelengths, using valves of the diode pattern. Pierret and Beauvais in France, and Carrara in Italy, have been responsible for work on communication systems which must not be overlooked. Then there is the practical work of the big commercial organizations in which are merged the corporate efforts of many individuals. Finally, credit must be given to the traffic-operating authorities who have had the courage to install equipment differing from normal practice in so many points of design and operation, and who have provided thereby the facilities for that long period of observation without which no sure knowledge as to propagation phenomena can be obtained.

For any who wish to study the historical development in greater detail an extensive bibliography is quoted at the end of the paper. A glance at the list of authors will suffice to show how world-wide has been spread the research which has gradually culminated in the modern micro-ray communication system.

(2) MICRO-RAY GENERATORS

The general theory of electronic and magnetron oscillators has been dealt with by E. C. S. Megaw in

two papers given before this Institution in 1933. It is not proposed to cover this ground again, but rather to treat in some detail the particular circuits employed on the commercial Lympne–St. Inglevert link.

The triode used contains electrodes which, from a comparison with the ordinary long-wave wireless valve, are often still referred to as "filament," "grid," and "plate." It will be shown later that no valvular action enters into the operation of the micro-ray generator and that the so-called "grid," which is formed of a wire helix symmetrically placed with regard to the filament, acts as a continuous transmission line. The "plate," also symmetrical with regard to "grid" and "filament," is a molybdenum cylinder. The words "valve," "grid," and "plate," therefore, as applied to this type of oscillator, are misnomers and have been replaced by "tube," "oscillating electrode," and "reflecting electrode" respectively, though the term "oscillating elec-
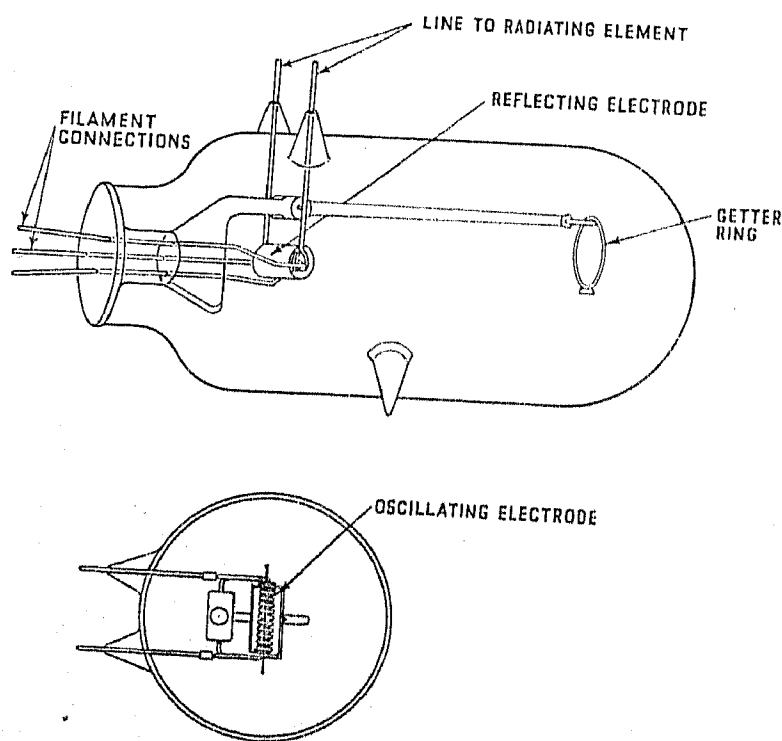

Fig. 1

trode" itself is not unimpeachable; "filament" and "cathode" remain as suitable terms for the electrode to which the heating current and negative H.T. battery are applied. The terms "grid" and "plate" have, however, the merit of being compendious, and in view of their general application to identify the cold electrodes with specific relation to their positions relative to the cathode their use has not been entirely eschewed in this paper. The "grid" or "oscillating electrode" has two lead-outs, which are connected to a transmission line, at a suitable point of which the load may be applied. Fig. 1 shows a micro-ray tube designed for use at 17 cm wavelength.

Let us take the concrete case of a tube oscillating at 17·4 cm with 275 volts (d.c.) on the "grid" or "oscillating electrode" and 95 volts negative on the "plate" or "reflecting electrode," these voltages being with respect to the cathode. The length of wire in the helix forming the "oscillating electrode" is 19 cm, the number of turns 17, the diameter of the helix 3·5 mm, the length of the glowing part of the filament 20 mm, and the

length of the cylindrical " reflecting electrode " 13·5 mm. The filament takes 3 amperes at about 4 volts, and the oscillating- and reflecting-electrode currents are 70 and zero mA (d.c.) respectively.

In approaching the question of why oscillations are generated we have the following clues given by experiment:—

(a) Oscillations occur for certain electrode voltages only. These voltages are always such that the filament is in saturation for the d.c. voltages applied; the generating force, then, acts during the saturation regime.

(b) No appreciable high-frequency current is found on the filament lead-outs. It is not possible with this type of oscillation to produce any change in output power by tuning the filament leads.

(c) The length of the glowing part of the filament is 2 cm, which represents less than $\frac{1}{8}$ wavelength. Inasmuch as the filament is connected to a mass of metal and to batteries and shows no trace of high-frequency current at its output terminals, it may fairly be regarded as a genuine earth busbar.

(d) The output circuit must be tuned approximately to certain wavelengths defined by the tube and the d.c. voltages used. The output circuit is most conveniently a transmission line to which a load is applied.

The transmission line formed by the oscillating electrode can maintain oscillations, provided its resistance or leakance per unit length is negative. There is no apparent reason why its resistance should become negative, so that the simplest explanation is that oscillations are generated because the oscillating electrode forms a transmission line of negative leakance.

How can such a negative leakance be explained?

Let us consider a tube whose output circuit has been detuned enough to prevent oscillation. A constant electron current leaves the filament, passes through the helical oscillating electrode, leaving a certain number of electrons on this electrode, is retarded, and is finally thrown back by the negative potential of the reflecting electrode. This returning stream of electrons again passes through the oscillating electrode, once more leaving a certain fraction of itself on this electrode, and re-enters the space between the filament and the oscillating electrode. We have, therefore, in the space between the wire helix and the reflecting electrode, two electron streams going in opposite directions. In the space between the wire helix and the filament we have three electron streams, one formed of the electrons that have just been thrown off the filament, the second made up of electrons returning towards the filament, and the third formed of returning electrons which have been reflected at the filament towards the oscillating electrode. The first and the third of these currents act in exactly the same manner. At every point, therefore, of the filament-oscillating electrode space there are electrons going towards the filament and electrons moving away from it. The electron current at any point is the algebraic sum of these two currents. Between the oscillating and reflecting electrodes the current is zero, while between the filament and the oscillating electrode the current is equal to the filament emission. The charge on the oscillating electrode will be substantially constant but may be expected to show very small variations on account

of irregularities of filament emission. Let us now adjust the tuning of the output circuit so that oscillations are maintained. The variations of oscillating electrode potential immediately rise to values compared with which the irregularities of filament emission may be neglected. The negative leakance caused by the mutual attractions and repulsions between the oscillating electrode charge and the electrons inside the tube is then a function of frequency, and since it is possible to obtain oscillations from diodes with voltage saturation, it is desirable to seek an explanation which does not depend on the third electrode.

A. G. Clavier[*] explains such a negative leakance by the variation of space-charge density produced by the speeding-up of electrons caused by any momentary increase of oscillating electrode potential. The electron which leaves the filament an instant after this extra oscillating electrode potential has been applied will be subjected to a greater accelerating force at any point of its " filament-grid " passage than were its fellow electrons which traversed this space before the grid potential was raised. It will therefore take less time to cover any distance. The oscillating-electrode potential does not, however, remain constant, and the electron just considered may gain on its fellows for part of the cycle and lose on them for the rest of its " filament-grid " journey. It may thus reach the oscillating electrode in less time than its immediate predecessors but with smaller final velocity. Thus the electron stream, which at the filament constitutes a constant current, reaches the oscillating electrode with a superposed alternating current whose power is derived from the reduction of the average kinetic energy of the electrons at the oscillating electrode. If the latter is tuned, so that a voltage shock produces a series of oscillations, and if the time taken by the electrons to traverse the " filament-grid " space is so adjusted that the superposed alternating current is out of phase with the oscillating voltage, the negative leakance so produced will sustain the oscillations, provided that the load and losses are not too great.

It is found by experiment that with any given transmission line and load the same frequency can be generated by the micro-ray tube for different pairs of values of oscillating- and reflecting-electrode potential, the output being different for every pair. For the optimum frequency and transmission line, it is possible to plot plate voltage against the grid voltage necessary to give the frequency chosen. Such a curve is shown by the dotted line in Fig. 2. If the output of the tube is measured for pairs of grid and plate voltages defined by the dotted curve, the full-line curve of Fig. 2 is obtained. Thus amplitude modulation of a substantially constant carrier frequency is obtained by the simultaneous variation of grid and plate potentials. By means of potentiometers it is an easy matter to apply modulating voltages to grid and plate in the necessary ratio to obtain a constant-frequency carrier, provided the grid voltage lies between 200 and 300 volts, i.e. on the straight part of the dotted curve of Fig. 2. The full-line curve of Fig. 2 shows that for straight-line modulation the grid voltage must lie between 240 and 300 volts. The d.c. voltage applied to the grid is,

[*] See Bibliography.

therefore, 270, allowing 30 per cent amplitude modulation.

The micro-ray tube, when used as a receiver, is adjusted to a non-oscillating condition. The signal to be received is applied to the " grid." Let us consider an electron which leaves the filament and is reflected before it reaches the reflecting electrode. If its initial velocity at the filament was zero and if the applied voltages are constant, it will come to rest at a point between the oscillating and reflecting electrodes where the potential is zero. The electron may, during its journey between the filament and the reflecting electrode, pick up an appreciable amount of energy from the signal applied to the oscillating electrode. If the voltage applied to the reflecting electrode is such that in the non-receiving condition those electrons that leave the filament with maximum velocity just fail to reach the reflecting electrode, an increase in the oscillating-electrode oscillating potential will increase the
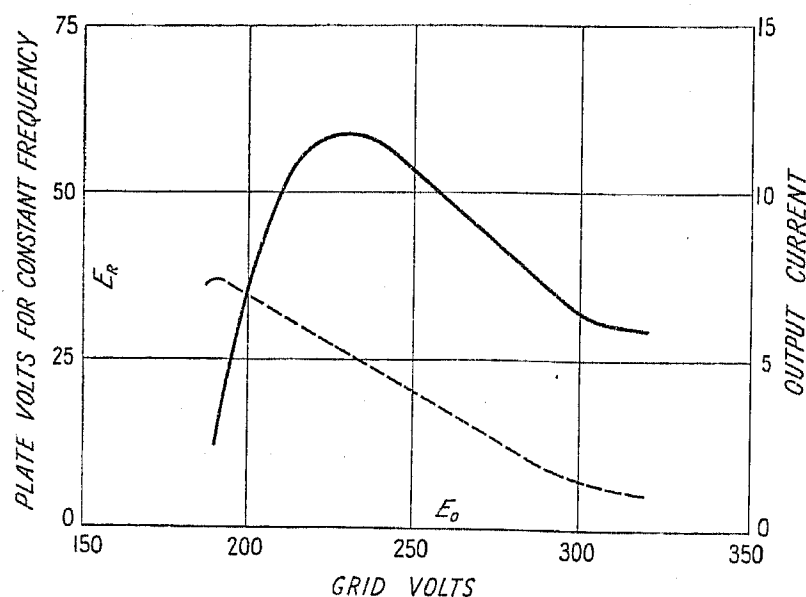
Fig. 2.—Relation of grid and anode potentials and variation of output for constant frequency.
Wavelength = 19·4 cm.

number of electrons reaching the reflecting electrode, while a decrease of oscillating electrode potential will not reduce the number. The average current in the reflecting electrode circuit therefore varies according to the amplitude of the micro-ray signal applied to the oscillating electrode. In other words, the essential detecting action of the micro-ray tube is produced by the one-way characteristic of the space between the filament and the reflecting electrode. Inasmuch as the electron current supplied to the tube from the filament is constant, a variation of reflecting-electrode current with modulation must be accompanied by an equal and opposite variation of oscillating-electrode current with modulation. The micro-ray receiver depends, therefore, on a valvular action in the tube, so that the term "valve" is not entirely inapplicable to the receiver tube. More important, however, is the amplifying effect, which is akin to reaction, since detection can be quite well effected by the use of a crystal or ordinary wireless valve detector of almost any type.

The optimum voltage values are necessarily functions of both the amplifying and the detecting actions, and in practice two optimum sets of adjustments can usually

be found, according to whether the amplifying or the detecting action is made to predominate. For example, with one particular valve and wavelength equally good reception was obtained with the alternative adjustments shown in Table 1.

Table 1

Adjustment	Grid voltage	Grid current	Plate voltage
1	155	6 mA	0
2	230	60 mA	— 55

The first set of adjustments corresponds to a predominance of the detecting action, and does not exhibit any frequency-selection property. The second corresponds to a predominance of the amplifying action, and is accompanied by marked selectivity in favour of the frequency to which the oscillating-electrode circuit is tuned. In both cases the filament emission is voltage-saturated, and reaction is controlled by a quenching oscillator (see Fig. 14).

(3) AERIAL SYSTEMS

Smallness of power is not necessarily a disadvantage to micro-ray communication, since at very short wavelengths large-gain radiation systems can be used. What system is to be preferred? The following possibilities immediately suggest themselves:—

(a) Wire aerial arrays.
(b) Lenses.
(c) Zone plates.
(d) Parabolic and paraboloidal mirrors.
(e) Echelon gratings.

(a) The technique of wire aerial arrays is well known, and their application to micro-ray presents no difficulty. A form of array adopted by one company consists of a number of parallel wire resonators spaced along and at right angles to a backbone of parabolic form which has an aperture of three wavelengths with an energizing aerial located at the focus of the parabola. The actual number of resonators used is in the neighbourhood of 60 and is determined by the required polar radiation diagram and gain. Such an array is definitely polarized parallel to the resonators, and the polarization of the radiated wave cannot be altered without rotating the array as a whole. The polar diagram includes one major lobe and a number of secondary lobes, whose presence may in certain circumstances become a nuisance. Such an array is governed in dimensions by the wavelength on which it is used, i.e. it is not aperiodic in the same sense as a mirror reflector. Moreover, in order to furnish anything in the nature of a sharp beam, it is necessary that the number of parallel wire resonators be increased from 60 to about 600. Considerations such as these, therefore, direct our attention to devices of less well known but more aperiodic nature, for example lenses.

(b) Sir Oliver Lodge seems to have been the first to demonstrate lens action with electromagnetic waves of micro-wave frequency, the results of his experiments being published in 1889. In view of the limitations imposed by the apparatus available at the time, the attainment of positive results in his researches was no mean achievement.

To obtain the data required in the design of radiation

systems for the micro-ray equipments later used in the 1931 Dover–Calais demonstration, a double convex lens was made of ebonite, formed for mechanical reasons of two similar plano-convex lenses with their plane faces stuck together (see Fig. 3). A vertical doublet C was employed as aerial, excited at a wavelength of 19 cm (see Fig. 4). In order to increase the strength of signal, a
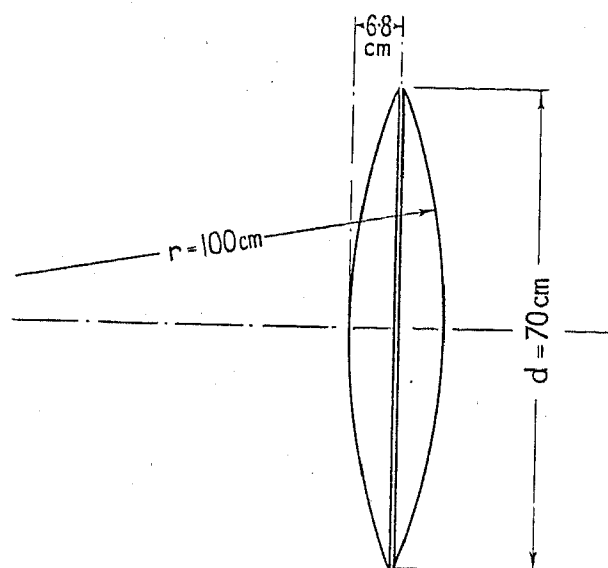

Fig. 3

plane metallic mirror D was placed at a distance of $\frac{3}{4}$ wavelength behind the transmitting element. A thermocouple E connected to a transmission line L was used as receiving element, and a metallic reflector F was placed on the transmission line and adjusted to the proper distance to give maximum thermocouple galvanometer deflection.

The thermocouple was moved along the axis of the lens and showed distinct maxima and minima situated

The fact that the focusing effect of the lens is somewhat obscured by diffraction naturally suggests the use of this latter effect as the major focusing means. We therefore pass to the use of zone plates, well known in optics.

(c) The principle underlying the design of zone plates is shown diagrammatically in Fig. 5(a). Let us consider an infinite surface ABCDE . . . A'B'C'D' . . . a section of which is shown in Fig. 5(a). Let us choose points BCDE . . . B'C'D'E' . . . so that TBR–TAR, TB'R–TAR, TCR–TBR, TC'R–TB'R, TDR–TCR, etc., each equal $\frac{1}{2}\lambda$.

Let T be a point source of wavelength λ. In order to determine the effect at any point of the radiation of T we can, applying Huyghens's principle, disregard T and consider every point on the plane EAE' as a new source whose relative phase and intensity are the phase and intensity (at the point) of the ray arriving from T. The intensity at R is the vector sum of the contributions from all the secondary sources on the plane EAE'. If P_1, P_2, P_3, etc., are points on the line AE so close together that the signal received from T may be considered constant from P_n to P_{n+1}, the total signal received at R may be determined by drawing the vector diagram shown in Fig. 6. It can readily be seen that the effect of all the rays passing between A and B is to produce a resultant signal at R of "ab," that the resultant (bc) of rays passing between B and C is substantially in opposition to "ab," and that adjacent zones have resultants substantially in opposition.

The argument applies to any section through T and R, so that the zones in three dimensions are as shown in Fig. 5(b). If the point T is at a great distance from A, the ratio of the lengths of TA, TB, etc., will be substantially unity, so that the secondary source at B will
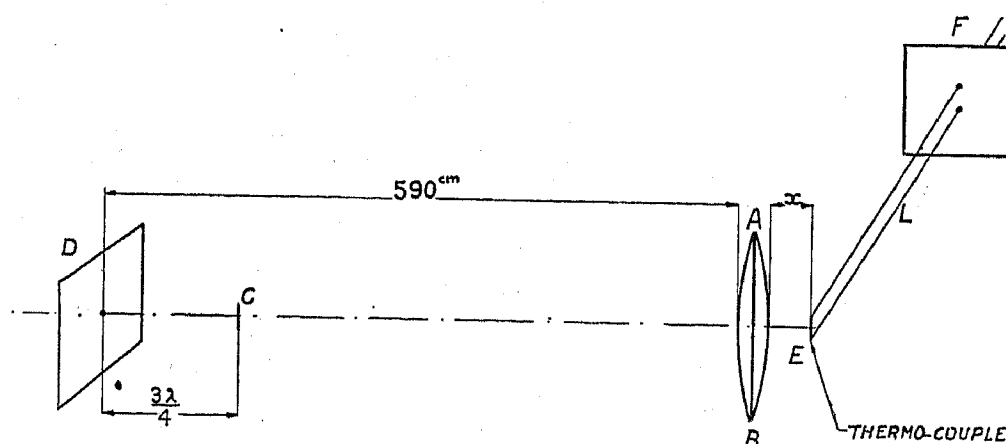
Fig. 4

at approximately $\frac{1}{4}$-wavelength intervals. The maximum obtained when the thermocouple was 40 cm from the lens surface was the largest and leaves no doubt as to the focusing effect. The subsidiary maxima and minima are probably due to diffraction. At 40 cm distance from the lens surface, the thermocouple gave a galvanometer deflection of 72. Upon removal of the lens this fell to 7. Inasmuch as the thermocouple deflections are approximately proportional to the power pick-up, it can be seen that the effect of the lens was to increase the received signal by some 10 decibels.

The same experiment repeated with one-half of the lens only, i.e. with a plano-convex lens, produced an image at a distance of 56 cm from the lens surface.

be of equal strength with the secondary source at A. In this case points b, c, d, e, in Fig. 6 lie directly above point "a," so that the radius vector "ap" passes through maxima and minima at b, c, d, e, etc. When, however, as is the case here, line TA is not of substantially the same length as line TB, b, c, d, e, in Fig. 6 are slightly displaced from the vertical through "a," on account of the unequal attenuation and obliquity of the rays. In this case a maximum resultant signal is obtained at R by slightly displacing BCDE towards A.

If an obstruction is put in the path of secondary rays coming from zones BC, DE, etc., it follows that the resultant signal at R will be increased. In a test zone-plate, made as shown in Fig. 5(b), aluminium rings,

represented by zones 0, 1, 2, and 3, in Fig. 5(b), were fixed on a 5-mm thick board made of wood. A doublet T excited at approximately 19 cm was placed 60 cm in front of the zone plate just described, and the resulting intensity at R, 60 cm behind the zone plate, was measured by means of a thermocouple (see Fig. 7). The galvano-
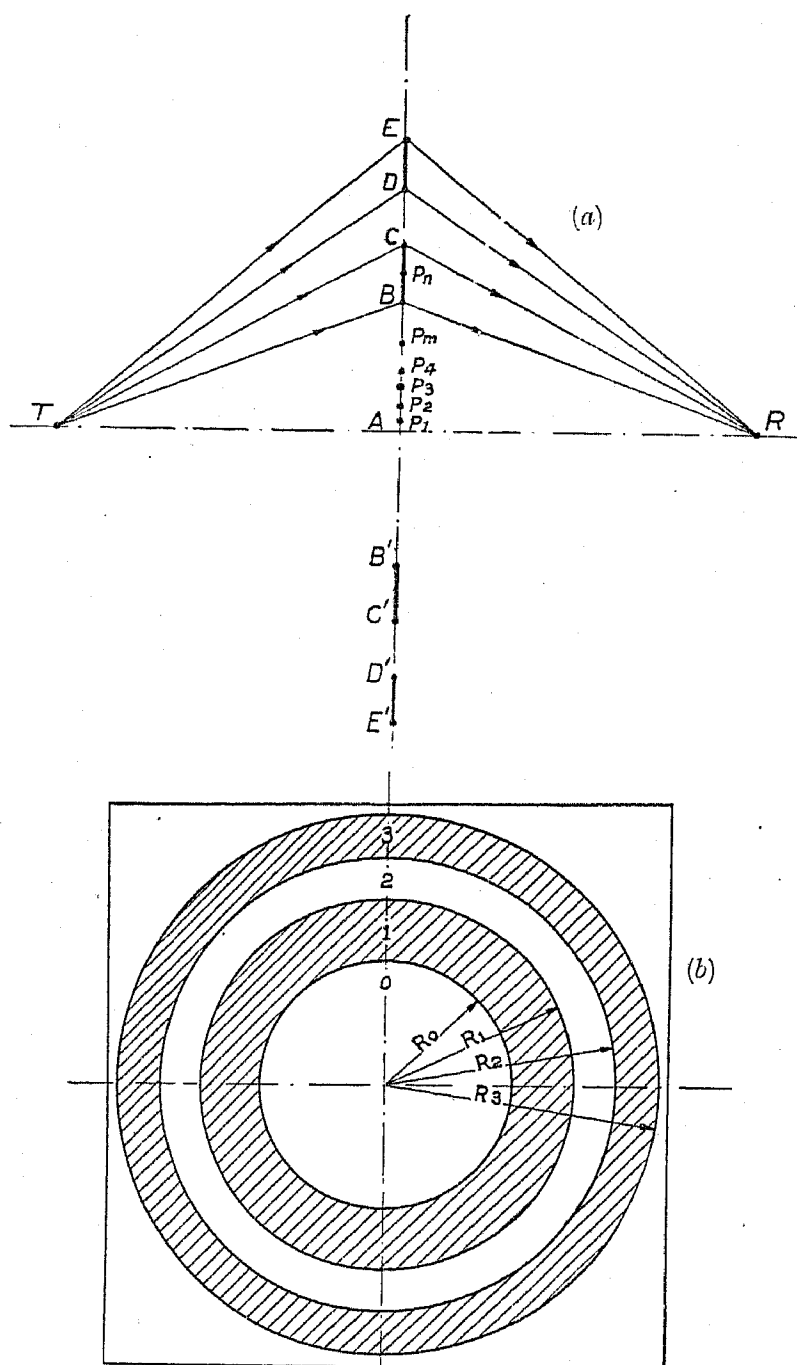

Fig. 5

In (b) $R_0 = 23 \cdot 5$ cm, $R_1 = 34$ cm, $R_2 = 42$ cm, and $R_3 = 50$ cm.

meter deflections (which are substantially proportional to the power received) were as follows:—

Zone plate entirely removed	19
Screen without aluminium rings	16
Screen with rings 0, 1, 2, and 3, in position	4
Screen with ring 0 removed	41
Screen with rings 0 and 1 removed	9
Screen with 0 and 2 removed but 1 and 3 allowed to remain	118
Wooden screen removed and rings 1 and 3 in place	139
Rings 1 and 3 removed, 0 and 2 and wooden board remaining	34

Thus this zone plate, 1 m in diameter, gives in this case a gain of 139/19, i.e. $8 \cdot 6$ db, at the point on to which it is focused.

The zone plates can clearly be used either by transmission of the signal from T to the point R or by its reflection to a point lying on the same side of the zone
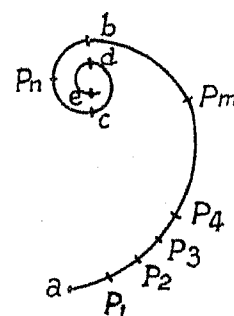
Fig. 6

plate as the doublet T. Fig. 8 shows the use of two zone plates dimensioned as in Fig. 5(b). One operates by transmission and the other by reflection to focus rays from a source T on to a point R. TA, the distance of the doublet from the first zone, being adjusted to the optimum value in each case, the power received at R for varying distances of RA' was measured. The maximum was distinct at RA' = 60 cm, giving a gain of approximately 10 decibels.

(d) It is clear, however, that the zone plate is wasteful of energy. Whether it is used by transmission or by reflection, the rays impinging on alternate zones are lost.
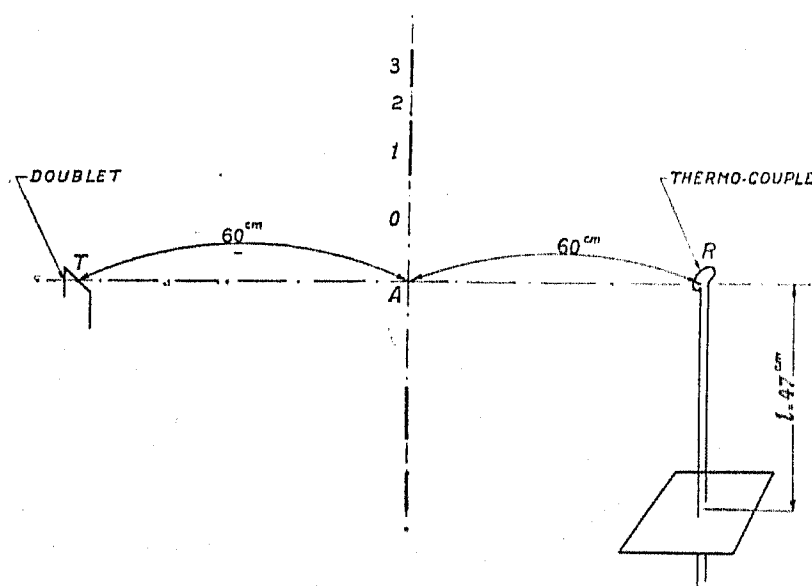
Fig. 7

Unless the diameter of the zone plate is infinite, the rays which escape outside the edges of the plate will be lost. It is possible by means of a spherical mirror, as will be seen later, to throw back on to the reflector all the forward radiation. It therefore seems logical to design some form of reflector which, by enclosing the transmitting antenna, intercepts all backward radiation. A reflector of parabolic section, with the radiator at the focus, immediately suggests itself, since all rays leaving the focus are parallel and of the same path length at a distance after reflection. A higher concentration of rays can clearly be obtained with a paraboloidal mirror than with a cylindrical parabolic mirror, as in the latter case rays may escape without reflection at the mirror. In

practice, the question arises as to where, for a given aperture of the paraboloidal mirror, the focus should be situated.

This question has been answered by R. Darbord,[*] who calculates the field at distance D to be:—

$$h = \frac{2\pi k}{\lambda D} \cdot \frac{pR^2}{p^2 + R^2}$$

where $k =$ a constant,

$\lambda =$ wavelength,

$\frac{p}{2} =$ focal length of the parabola,

and R is the radius of the aperture of the paraboloid.

He further determines, by calculation, the lines of equal intensity on the paraboloid. The projections of these equal-intensity lines on the director plane are shown in Fig. 9. The interpretation of this figure is that an element of the paraboloid, situated on a line whose projection on the director plane is marked 0·5, contri-
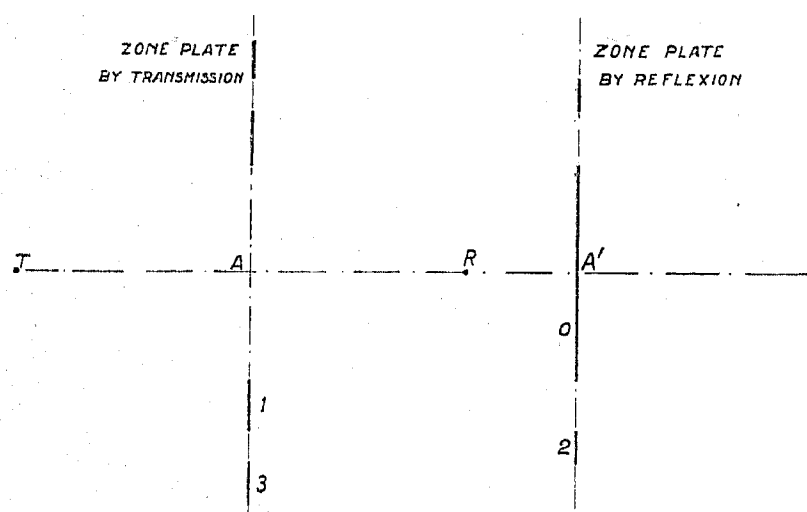
Fig. 8

butes to the field at a distance along the axis of the reflector 0·5 of the field contributed by an element situated directly behind the antenna, provided the projected areas of these two elements are equal; the hatching denotes surfaces whose contribution tends to reduce the resultant field at a distance along the axis of the reflector, with the result that the beam is wider in the plane of symmetry through the radiator than in the plane of symmetry at right angles thereto. As shown in a later section of this paper, the beam width is $\pm 3\cdot7°$ and $\pm 2\cdot2°$ in these planes respectively for a 10 db loss of audio signal. The measured gain along the axis is between 22 and 23 db.

The existence of destructive areas can easily be shown. Fig. 10 represents a symmetrical section of the paraboloid through the focus, the radiator AA′ being in the plane of the paper. Let P and P_1 be two points, one on the left and one on the right of the focal plane. If we represent the polarization at the radiator by A′A, the ray striking the reflector at P will excite currents in the conducting surface of the reflector in the direction PQ, where Q is the point of intersection of A′A and the tangent at P. This has a component proportional to MQ, where PM is perpendicular to A′AQ. A ray,

* See Bibliography.

incident on the reflector at the point P_1, will, however, excite an elementary area at P_1 in the direction P_1Q_1 which has a component proportional to M_1Q_1. It can be seen from the figure that MQ and M_1Q_1 are in opposition. The change of phase in the path SPR being
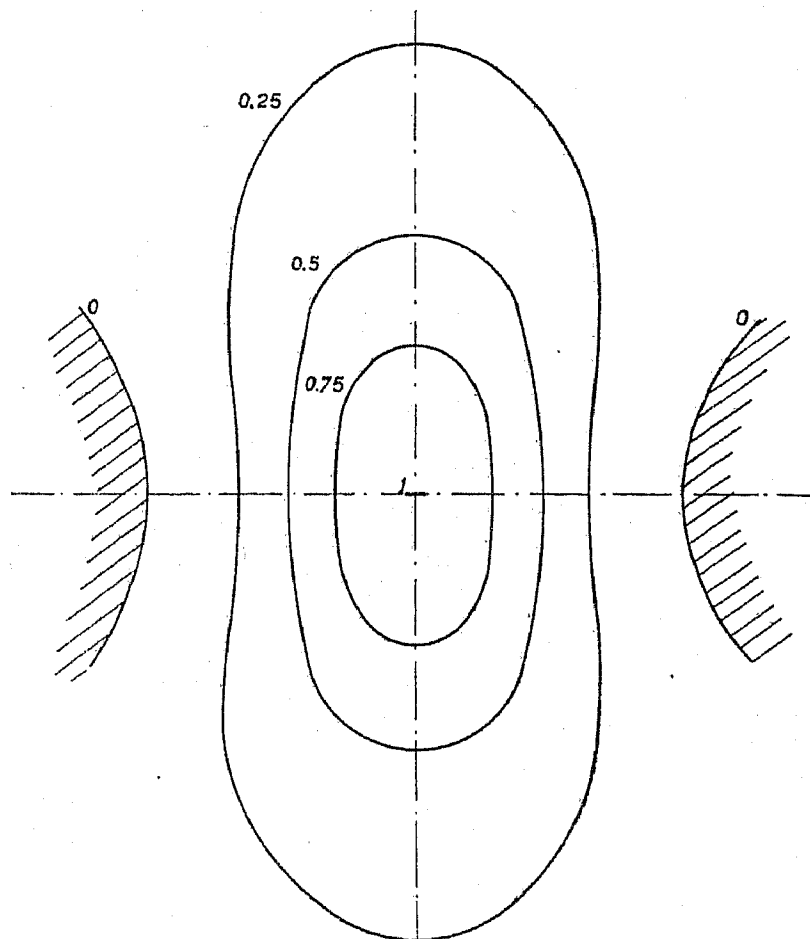
Fig. 9

exactly equal to the change of phase in the path SP_1, the contributions to the signal at a distance along the axis are of opposite sign for elementary areas situated at P and P_1.

The locus of points of zero intensity is the locus of points T on the paraboloid where the plane through the antenna and the point T cuts the tangent plane at T
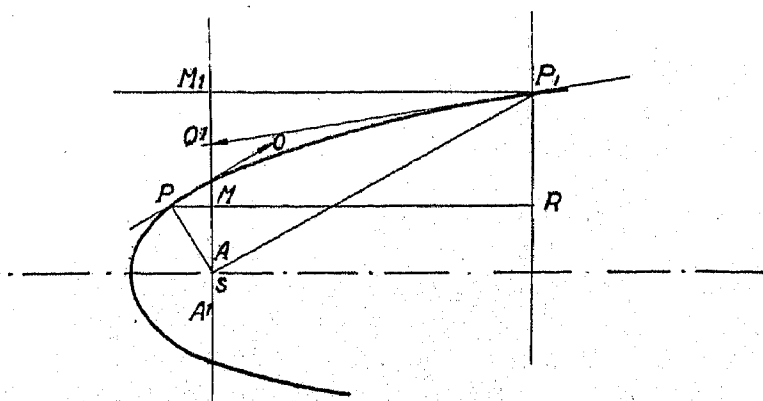
Fig. 10

along a line which is itself perpendicular to the antenna. In this case the contribution of an elementary area at T to the field at a distance along the axis of the reflector has a polarization perpendicular to that of the radiator and, as by symmetry the resultant polarization at any distant point situated on the axis is the same as that of the antenna, the contribution at T to the useful signal is zero.

It would, of course, be possible to nullify the effects of the hatched destructive areas by cutting away these parts of the reflector; alternatively, the reflector surface might here be displaced towards or, preferably, away from the focus, so as to decrease or increase the length of path of a ray incident on the reflector within these areas by half a wavelength. The mechanical complication would, however, not be justified, as the hatched areas are, in general, areas of low intensity.

Unless any such changes are made in the reflector, it follows, from the equation given above, that the distant signal will be a maximum if $p = R$; that is to say, if the aperture of the parabola is the focal plane. In these circumstances Darbord shows that the gain of such a paraboloidal reflector is equal to half the number of wavelengths in the circumference of the aperture.

It is interesting to compare paraboloidal mirrors with wire arrays. Let us assume a plane wire array made up of n stacks of m half-wave elements separated half a wavelength. There will then be mn elements and the gain over a single half-wave element will be $\sqrt{(mn)}$, on the assumption that the losses in the wires joining the half-wave elements are negligible. The area covered by the system is $\frac{1}{4}\lambda^2 mn$, allowing a distance of $\frac{1}{4}\lambda$ on each side of the extreme half-wave elements as being included in the antenna area. By application of Darbord's rule, the area of the aperture of a paraboloidal reflector giving a gain of $(\sqrt{mn})$ would be $(\lambda^2 mn)/\pi$. The area of the aperture of the paraboloid is therefore $4/\pi$ times as great as the area of a plane array giving the same gain. In practice, the advantages of the paraboloidal mirror are very distinct. A paraboloidal reflector of 3 m diameter gives a voltage gain of 25 at 18 cm wavelength. An array giving equal gain will consist of 625 elements, and the losses in transmission lines at micro-ray frequencies are so great that it would probably be difficult to obtain an efficiency as high as 50 per cent, since the insulators holding the half-wave elements in position cannot conveniently be placed at voltage nodes. With the normal type of high-mast wire antenna as used in the 12- to 50-m range, phase-changers are placed in the vicinity of the voltage antinodes. The displacement of mycalex insulators from the voltage nodes to near the antinodes necessitated by such a construction, would in the case of a micro-ray transmission line introduce a loss of at least 1 db per insulator at 17·4 cm if the insulators were dry. Should the insulators be wet, considerably higher losses would be obtained. The paraboloidal mirror has the advantage of being mechanically strong and requiring no modification in case of change of wavelength or polarization.

(*e*) A type of reflector which may be considered to be a hybrid between a zone-plate system and a paraboloidal mirror will now be described and referred to as an "echelon grating." It is made up of portions of paraboloids having the same focus but focal distances differing by half a wavelength or a multiple thereof (see Fig. 11, which shows a section in a plane of symmetry). In accordance with geometrical optics, rays from the focus incident on any one of the paraboloidal surfaces will be parallel to the axis and, if the focal distances are properly chosen, in phase at the distant receiving station. For practical purposes each portion of parabola, as seen

in the section shown in Fig. 11, may be replaced by a straight line, so that in practice the echelon grating consists of a number of truncated cones with a flat portion in the centre. The truncated cone is a surface which is more easily made than a paraboloid, as it can be developed, whereas the latter must be spun, moulded, or hammered out, on a paraboloidal surface. The different portions of truncated cones may be easily fixed to a wooden board. The diameter of the central portion and the lengths of the lines a, b, c, d, etc., of Fig. 11, are defined by the loss which it is permitted to incur as a result of the replacement of the paraboloidal sections by portions of truncated cones. It is to be expected that the gain given by such a reflector would be less than that of a paraboloidal mirror, on account of the fact that an appreciable part of the antenna radiation may escape without impinging on the echelon grating, even though a hemispherical mirror in front of the radiator be used. From the same considerations as those which
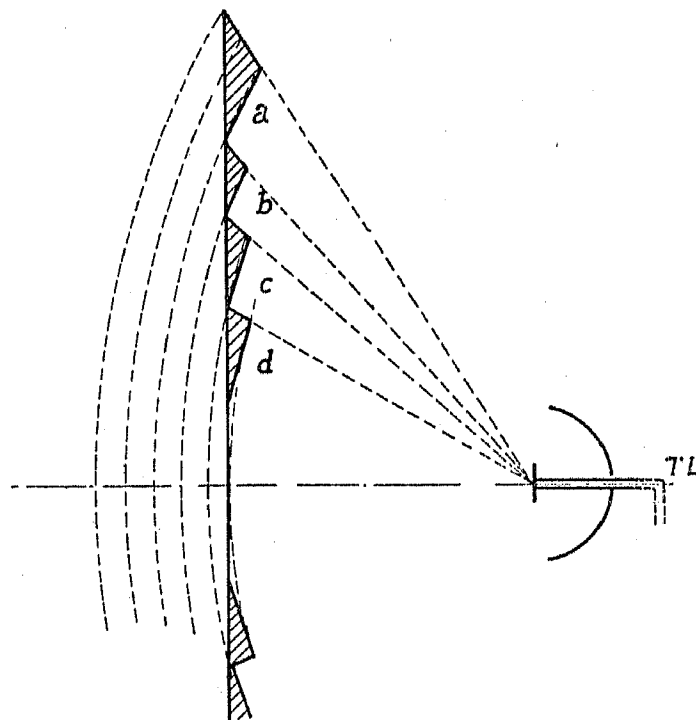

Fig. 11.—Section of echelon grating.

apply to the paraboloidal-mirror case it would be expected that the beam width would be greater in the plane of symmetry through the radiator than in the plane of symmetry at right angles thereto. The measured width in these planes of a 4-m diameter grating was $\pm 5°$ and $\pm 3°$ respectively at 18 cm wavelength for a 10 db loss, and the gain along the axis was approximately 15 db.

It will be seen that whether a paraboloidal reflector or an echelon grating is used, practically all the radiation which leaves the antenna in a forward direction never reaches the distant station. This loss of power may be overcome by the use of the hemispherical mirror placed in front of the antenna, so as to throw back all the forward radiation on to the reflector situated behind the antenna. In order that these forward rays should reach the reflector in phase with the backward rays, it is necessary that they should be subjected to a phase change of 360° or a multiple thereof. Allowing for a phase change of 180° at reflection at the hemispherical mirror, we should at first conclude that the radius of the latter would have to be an odd

multiple of a quarter-wavelength. Here, however, a curious phenomenon, well known in optics, is encountered; it is known as the Gouy effect, after its discoverer. The rays reflected by the hemispherical mirror are accelerated in phase, so that after passage through the focus the phase has been advanced by 180° more than would normally be accounted for by path length. For this reason the radius of the hemispherical mirror must be a multiple of a half-wavelength.

The effect of the hemispherical mirror being to throw back on to the paraboloidal reflector power equal to that which would be incident on the paraboloid if the hemispherical mirror were not used, it might be expected that a gain of 3 db would be measured. In practice it is difficult to obtain a precise figure, since the introduction of any reflecting element near the radiator changes the impedance of the antenna and so involves readjustment of the associated circuits. An average value of the measured gain due to the hemispherical mirror is 3 db.

While the performance of reflecting systems has so far been discussed from the standpoint of transmission, the argument, by virtue of the reciprocity theorem, will apply equally to reception. This is confirmed by experiment.

(4) EQUIPMENT

Two two-way circuits have been established across the Straits of Dover. The first was an experimental link, installed in February, 1931, between the terminal stations of Escalles near Calais and St. Margaret's near Dover, while the second was a commercial link connecting the aerodromes of Lympne and St. Inglevert.

The equipment of a micro-ray station can be grouped into the following main divisions:—

    (a) Aerial and reflector system for transmission.
    (b) Aerial and reflector system for reception.
    (c) Generating circuits for transmission.
    (d) Detecting circuits for reception.
    (e) Control equipment.
    (f) Power supplies.

Items (a) and (c) above are necessarily located close together, as are also (b) and (d), since it is inadvisable to have very long connections (long as measured by the number of wavelengths) between the micro-ray tube and its associated radiating or receiving aerial. This holds good for all micro-ray tube circuits, and for all aerial and reflection systems of no matter what type. The location of items (e) and (f) is, however, governed by convenience and cost, rather than by purely electrical considerations, and may be at a considerable distance from other parts of the system. The practical points involved are well illustrated in the installation of the Lympne–St. Inglevert link, which not only uses the shortest wavelength of any commercial station in the world—17·4 cm—but also constitutes the longest micro-ray circuit in regular operation up to the present time.

The English terminal of this link was built to Air Ministry order by Messrs. Standard Telephones and Cables, Ltd., while the French terminal, to the order of the French Air Ministry, was built by Le Matériel Téléphonique of Paris. The two firms naturally worked in close co-operation, and the terminals are substantially similar in basic design, though differing in matters of detail governed by local station conditions and country of manufacture. The distance between the two stations is 56 km (35 miles), the radiating and receiving aerials being mounted at such heights as to give an unobstructed, geometrically straight path (i.e. what is rather loosely referred to as an "optical" path) between them. In order to facilitate duplex operation, slightly different wavelengths are used in the two directions, with physically separate transmitting and receiving aerial and reflector assemblies. The difference in wavelength is about 0·5 mm, which sounds very small; but it corresponds to a frequency separation of 5 000 kc.

As regards the purely micro-ray side of the equipment, the aerial and reflector assemblies at both ends of the link are similar in construction and are based on the optical reflector principle instead of the orthodox aerial array. The aerial is of the half-wave dipole pattern, located at the focus and in the aperture of a paraboloidal aluminium mirror reflector some 10 ft. in aperture diameter, spun from aluminium sheet approximately 0·2 in. thick. To the periphery of this reflector is riveted an aluminium ring which serves to keep the spun metal rigid and undistorted. The aerial is carried on the end of a very rigid tubular transmission line which traverses the body of the reflector and is energized from the micro-ray tube. This latter is mounted in a cylindrical weatherproof housing carried on the back of the reflector. In addition to the main paraboloidal reflector, a small auxiliary aluminium hemispherical reflector is also used; this is carried by three wooden supports springing from the edge of the paraboloid, and is so located that the apertures of the two reflectors are central and co-planar. The object of this hemisphere is to reflect the direct forward radiation from the aerial doublet back to the paraboloidal reflector so as to incorporate its energy in the beam, increasing the gain of the reflecting system by 3 db. In order to obtain correct phasing, the diameter of the hemispherical reflector must be a multiple of a half wavelength, as explained elsewhere in the paper, and in the present case corresponds to 3 wavelengths. The main reflector gives a gain of about 28 db on the operating wavelength. Its aperture is approximately 18 wavelengths, but is not critical with regard to wavelength; in this respect the paraboloidal reflector differs definitely from the hemispherical reflector and the "array" type of reflector, the dimensions of both of which are functions of the wavelength. In addition to its electrical function, the hemispherical mirror serves to some extent the purpose of protecting the aerial against weather, particularly against the deposit of snow.

In view of the large superficial area of the reflectors, it is obvious that wind loading is the determining factor in the method of support. The entire reflector assembly is carried on a strong steel framework, which in turn is firmly bolted to a steel tower. In the case of the Lympne installation it was found possible to build the towers round the terminal piers of a hangar, giving a remarkably solid structure. Separate towers are used for the transmitting and receiving reflectors, with 200 ft. separation between them—an arrangement which is advantageous in reducing cross-talk at micro-ray frequencies. Access to the reflector assemblies is by means of iron ladders leading to a wooden platform. At the rear

of the reflector, a large metal cowling provides some shelter for the operator when changing a tube or other adjustment is necessary. Directional adjustment of the reflector is made during installation, and is subsequently verified or corrected slightly if necessary by means of regulating devices on the main framework, which permit the axis of projection to be moved through an angle of $\pm 5°$ in both the horizontal and vertical planes.

At St. Inglevert, the buildings available did not lend themselves to the same type of tower structure as was used at Lympne, and recourse was therefore had to a self-supporting lattice tower of height 60 ft., on which both transmitting and receiving reflectors are mounted side by side on a common platform. Tests have shown that while, owing to the proximity of the reflectors, there is definitely a greater amount of micro-ray frequency cross-talk than at Lympne, it is still too small to create any operating difficulties. This single tower, carrying the load of two reflectors, is, of course, subject to greater windage than the structure at Lympne, and in high winds a certain amount of swaying of the top is noticeable; this, however, does not alter the angle of projection of the beam to any appreciable extent, and has never been found to affect either the transmitting or the receiving channels.

The tubular transmission line which feeds the aerial includes a portion whose length can be varied telescopically in order to provide correct impedance matching between aerial doublet and tube. The inner conductor is supported at voltage nodes by means of mycalex insulators. All surfaces carrying micro-ray frequency currents are gilded by a galvanic process in order to minimize corrosion, and other parts are painted with special weather-resisting paint as a protection against the unfavourable weather conditions which prevail near the sea coast.

Transmitting and receiving aerial, reflector, and tube assemblies, are identical except that the transmitting reflector carries an auxiliary aerial, fairly close to the surface of the paraboloid and connected by a short transmission line to a thermocouple which energizes a micro-ammeter in the control room and corresponds to an aerial ammeter. As the sensitivity of the arrangement is a function of the impedance matching between the auxiliary aerial and the thermocouple through the transmission line, by adjustment of the latter for maximum deflection of the microammeter it is possible to calibrate the optimum length of the transmission line against wavelength and so obtain a wavemeter on the Lecher-wire principle. Additional control over the meter reading can be obtained by rotating the auxiliary aerial and thereby altering its coupling to the main aerial.

A special advantage of the optical system of reflectors as compared with the array is that the plane of polarization of the beam is uniquely determined by the plane of the dipole element, which can easily be rotated. Advantage has been taken of this on the Lympne–St. Inglevert link to operate the two channels on different planes of polarization, thereby still further reducing the possibility of cross-talk. The Lympne–St. Inglevert channel is operated with a horizontally polarized wave, the other channel being operated with a vertically polarized wave, and the transmitter and receiver aerial doublets are accordingly horizontal and vertical respectively at the Lympne end of the link. There is no particular merit

about this selection of planes of polarization; any two planes at right angles would give the same benefits.

Power Supplies and Control Equipment

The frequency of a tube micro-ray generator is sharply dependent on the electrode voltages, and stability of power supply is therefore of extreme importance. One solution is to use batteries. This solution, however, is not without its disadvantages from the standpoint of maintenance, and preference would normally be given to direct generation of the required d.c. voltages either by machines or by rectifiers—a system which would be satisfactory provided that the power mains supply voltage was well regulated. In the case of Lympne the 220-volt d.c. mains supply is furnished by a small local power station, and the regulation is normally good, but when the aerodrome's neon-tube beacon comes into operation, flashing the morse signal "A" once every 2 seconds or so, the keying of the beacon involves such abrupt and considerable changes in the total station load that the regulation becomes distinctly bad. It was originally planned to take all power supplies, except that for filament heating, from a motor-alternator fitted with an automatic constant-voltage regulator, but it was found that the periodicity of the beacon signal elements was too close to that of the automatic regulator to permit of its satisfactory operation. Recourse was finally had to the use of small 3-ampere-hour floating batteries connected through rheostats across the outputs of the dry rectifiers supplying the micro-ray tube plate and grid d.c. potentials.

This arrangement gives an excellent degree of stability with very little extra maintenance. Attention to the batteries is confined to periodical "topping up." As the batteries do not actually furnish power, there is no question of change of voltage under charge and discharge conditions, and the combination of mains furnishing the actual steady supply and battery for absorbing momentary fluctuations has proved itself rather more convenient in practice than the use of batteries alone.

It is quite possible that the use of floating batteries might have been avoided altogether and their place taken by "constant voltage" gas-discharge tubes. At the time the station was installed, however, no tubes of suitable voltage and current capacity were available in this country; and in any case there was some doubt as to the constancy of the operating voltage of such tubes over a period of hours, whereas the performance of batteries was well established. Such gas-discharge tubes have since been used in other cases (not micro-ray stations) with excellent results, but it still remains undetermined as to whether they would prove definitely superior to small floating batteries where micro-ray working is concerned.

Current for filament heating is obtained from an accumulator battery, operated on the charge-discharge principle. In this case no attempt has been made to operate the battery in the floating condition, owing to the risk of noise being set up in the micro-ray circuits, particularly the receiver. Stability of filament current is possibly even more important than stability of plate and grid supplies. Since the micro-ray tube is operated under the condition of saturation, any change in filament

current is accompanied by a change in space current which in turn causes a change of distribution of the potential-drop along the grid-feed potentiometer, and hence of the grid potential and the operating wavelength. It is therefore essential that the filament battery be maintained in as good condition as possible, operated well within its rated capacity, and fully charged, i.e. up to about 2·7 volts per cell, every 24 hours. When put on load it is necessary to allow a stabilizing period of 10 to 15 minutes, during which time the battery voltage falls

filament battery, while others are of the indirectly heated type energized by alternating current from the mains. In both cases the teleprinters and associated voice-frequency units are energized by alternating current drawn from the motor-generator or from the mains.

The power efficiency of this type of station is unfortunately very low. While the micro-ray input to the aerial is estimated at about 0·5 watt, the filament wattage alone is 15 watts per micro-ray tube. The filament supply itself is taken from a 12-volt battery feeding
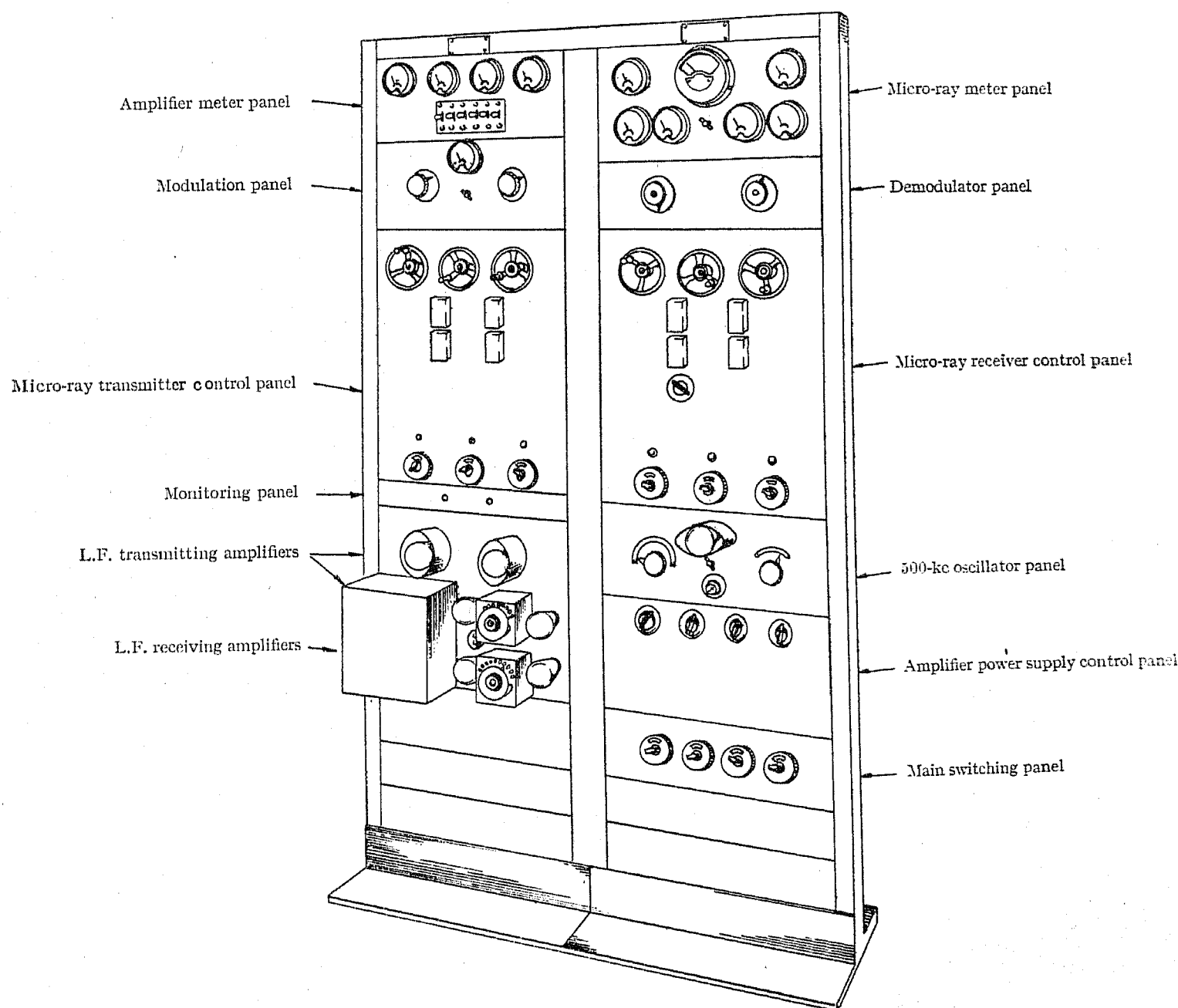
Fig. 12.—Micro-ray control bays at Lympne.

by about 0·1 volt per cell, even although it has been taken off charge for some hours previous to being put on load.

Power supplies for apparatus other than the micro-ray tubes present no special problem, and are taken from whatever source is most convenient—main filament battery, alternating current from the motor-generator, and high-tension direct current from a dry rectifier without floating battery. It so happens that all the valves used at Lympne are of the directly heated type and take their cathode heating from the main filament battery. At St. Inglevert some of the valves are of the directly heated type with cathode heating drawn from the main

4·5-volt valves, the margin of voltage being necessitated primarily by the long cable-runs and secondarily by the need for providing some margin for regulating purposes, so that the actual filament-circuit consumption is approximately 85 watts. At both transmitter and receiver the grid dissipation in the micro-ray tube is of the order of 20 watts, obtained through potentiometers involving a further loss of 80 watts. The combined gross power consumption of transmitter and receiver (exclusive of low-frequency amplifiers, etc.) is therefore in the neighbourhood of 250 watts. The magnitude of this figure is to a considerable extent due to the desire to use simple methods of control and apparatus of common

experience, and might well be reduced by turning to new types of apparatus and more complicated feed circuits. It is fortunate that the extremely high efficiency of the reflecting aerial systems easily compensates for the low power efficiency. In the case in point, the total transmitting reflector gain is about 31 db, and the aerial input of 0·5 watt gives a signal field corresponding to over $\frac{1}{2}$ kW in an omnidirectional aerial. The question of power efficiency is therefore much less serious than might appear at first sight.

The control equipment proper is panel-mounted on a 2-bay rack and provides facilities for switching, metering, and adjusting, the various power supplies. It also includes the audio-frequency amplifiers for both transmission and reception, and the 500-kc oscillator which is used in connection with the micro-ray detector. The layout of the bays as installed at Lympne is shown in Fig. 12. Sufficient amplification is provided to enable the equipment to be fully driven with a modulating signal (speech or tone) about 20 db below 1 milliwatt, and to furnish an audio output as high as 10 milliwatts if necessary. These circuits all follow orthodox commercial practice, and call for no particular comment. Included in the metering facilities is a "modulation indicator" consisting of a 2-range rectifier-type voltmeter whereby the amplitudes and ratio of the modulating voltages delivered to the plate and grid of the micro-ray transmitting tube can be measured. As the meter reads only r.m.s. values, it does not constitute an effective guide to the *depth* of modulation except when the input is a pure tone; but since its fundamental use is for lining-up the circuit this disadvantage is of no material importance. Plate negative bias and grid positive high tension are adjusted to the correct values by means of individual potentiometers, separate potentiometers being provided for transmitting and receiving tubes.

Transmitting System

A simplified circuit diagram of the transmitting system is shown in Fig. 13. The condensers C_1 serve to keep the d.c. supplies off the modulation potentiometer circuit, and are of 4-μF capacitance. Choke coils L_1 serve to prevent the modulation voltages from being dissipated in the d.c. power supply networks. Condensers C_2 isolate the aerial transmission line assembly from the H.T. supply to the grid; they are of very small capacitance, a few micro-microfarads only, with mica dielectric, and are formed by the capacitance between a nut on each of the two grid extension rods and the transmission-line terminal plate, through which the extension rods pass freely and without metallic contact. It will be noticed that there are no chokes to prevent loss of micro-ray energy in the power supply leads, as the latter themselves present a high impedance at these frequencies. It will also be noticed that the thermocouple of the radiation indicator has only one pair of wires—i.e. instrument and heater wires coincide. The lengths of both the main and the thermocouple transmission lines are telescopically variable over approximately $\frac{3}{4}$ wavelength.

The micro-ray tubes used in this station are of the so-called "spiral grid" type, for both transmission and

reception. They resemble in external appearance the old " R " valve, in having a straight filament, helical grid, and cylindrical plate. The grid has the special feature that, in addition to being led out at both ends, it has no longitudinal strengthening members, and is dependent for its rigidity on its construction as a helix and the physical properties of the wire of which it is made. The power dissipated at the grid is of the order of 20 watts, which raises its temperature to a white heat, and it is obvious that the construction of such a helical grid to meet the condition that it shall be without appreciable sag or other distortion at the operating temperature, introduces rather special manufacturing problems. So far only tungsten filaments have been used, the governing requirements being not only that the emission shall have a certain value, but that the filament
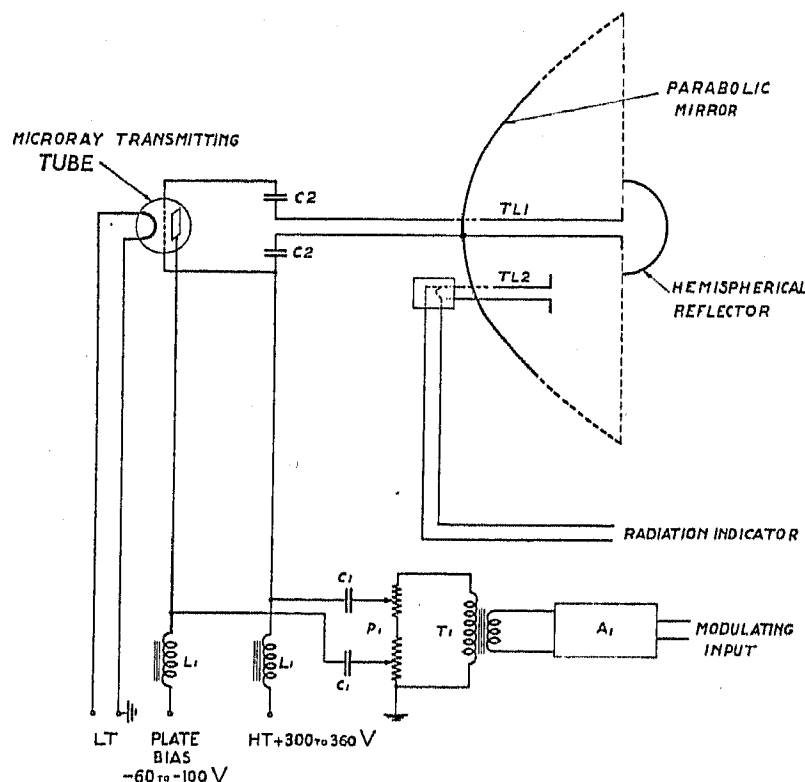

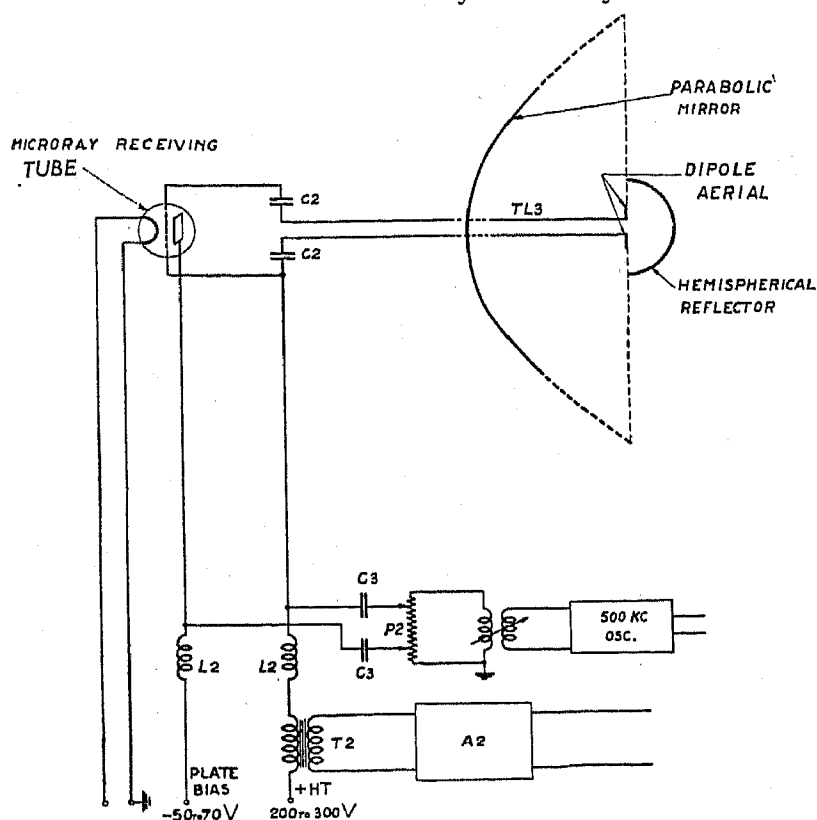**Fig. 13.**—Simplified schematic diagram of Lympne micro-ray transmitter.

P_1 = modulation potentiometer; T_1 = modulation transformer; A_1 = 3-stage audio-frequency amplifier (max. gain 50 db); TL_1 = tubular transmission line to radiating aeria ; TL_2 = tubular transmission line to thermocouple.

saturation point shall be well defined. This latter condition, of course, precludes the use of coated filaments, despite their advantages when the governing requirement is only the total emission. The theoretical life of the tube, as determined by the filament operating conditions, is about 1 000 hours, and in practice the life is found to be between 700 and 900 hours.

As has already been remarked, the control equipment may be some distance away from the purely micro-ray portion. At Lympne the micro-ray transmitting tube and associated circuits are about 250 ft. of cable run from the control bays, to which they are connected by 6 wires —2 filament leads, grid high-tension, plate bias, and 2 thermocouple leads. All are lead-covered except the filament cables, the braid insulation of which has to stand only a very small potential to earth, not exceeding 12 volts. It will be understood that the power leads, in addition to carrying the d.c. feeds, also carry the audio-frequency modulating potentials.

Receiving System

A corresponding simplified circuit diagram for the receiving side is shown in Fig. 14. This is very similar to that of the transmitter, except that the modulation source is replaced by a 500-kc quenching oscillator, and that the chokes L_2 in the plate and grid power circuits are effective at 500 kc instead of at audio frequency, while the grid high-tension supply circuit includes the primary of an output transformer which feeds the receiving-side audio-frequency amplifier. The distance from the control bay to the receiving micro-ray tube and associated equipment is in this case about 70 ft., and 4 single conductors are run from the bays to the valve housing. In addition to carrying the power feeds, these cables have also to carry not only the detector

Fig. 14.—Simplified schematic diagram of Lympne micro-ray receiver.

P_2 = demodulator potentiometer; T_2 = demodulator transformer; A_2 = 2-stage audio-frequency amplifier (max. gain 40 db); TL_3 = tubular transmission line to receiving aerial.

audio-frequency output but also the 500-kc potentials. No attempt has been made at feeding the 500 kc potentials to the tube through a separate transmission line, as the oscillator has sufficient output to give the necessary voltage at the valve electrodes, despite the heavy loss in the lead-covered cabling.

Communication over the Lympne–St. Inglevert link is always on a tone-modulated basis; the tone may be either telephony or oscillator tone of 3 500 cycles per sec., keyed for morse telegraphy if desired, or controlled by the signalling contacts of a Creed teleprinter. The frequency stability of the micro-ray generators is not, with such simple circuits, sufficiently good for regular c.w. operation, although with a little care it was quite possible to obtain an audible beat note even at micro-ray frequencies. The oscillator tone is of unusually high frequency, and was selected to permit possible combination of speech and teleprinter working at a later date, with separation of the two channels by audio filters. For teleprinter working—which is the usual method of com-

munication between the two stations—a band-pass filter is inserted in series with the output from the receiving amplifier, passing the receiving tone on to the voice-frequency unit which converts the tone pulses into d.c. pulses for operating the printer relay, and attenuating the residual receiver mush which would otherwise give steady bias to the printer relay and cause faulty operation. It should perhaps be mentioned that the combination of teleprinter and voice-frequency unit is, except for apparatus changes involved by the use of 3 500-cycle instead of 350-cycle tone, identical with the teleprinter equipments now regularly operated through the Post Office " Telex " network in all parts of the country, and is designed to carry traffic at the rate of 66 words per minute. The printer is of the latest Creed 7A–8A pattern, adapted for tape recording, with English keyboard arranged to line up with the French keyboard at St. Inglevert.

Since the installation of the Lympne–St. Inglevert link, a new type of receiver, due to A. G. Clavier, has been evolved. A circuit diagram is given in Fig. 15. It will be seen that the oscillating electrode circuit of the receiving micro-ray tube, instead of the low-frequency transformer formerly used, contains a circuit tuned to an intermediate radio frequency. This radio frequency in one commercial model was 100 kc. The 500-kc stabilizing oscillator used in the Lympne–St. Inglevert equipment is not necessary. A dynatron effect in the micro-ray tube causes the tuned circuit to produce 100-kc oscillations, on which the modulation of the incoming micro-ray frequency is impressed. A commercial radio receiver
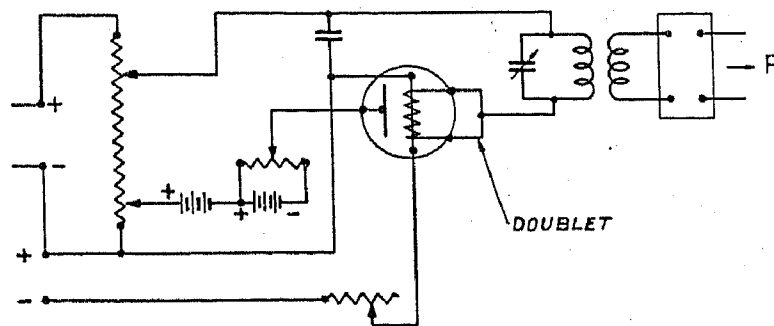

Fig. 15

tuned to this intermediate frequency and coupled to the 100-kc tuned circuit will give at its output a signal/noise ratio appreciably better than that obtained with the simpler Lympne–St. Ingelvert type of receiver. The signal/noise ratio gain depends on the intermediate frequency used. Observations made at St. Inglevert over a period of 6 months show that for an intermediate frequency of 100 kc the signal/noise ratio gain is 6 db. A further advantage is obtained from this new receiving method in that the adjustment of the micro-ray tube voltages is much less critical and that an automatic gain control on the intermediate-frequency equipment may be used to counteract in a large measure fading effects.

The permissible variation of the grid voltage in the case of the double-detection method of reception is ± 6 per cent for the receiving and ± 7·5 per cent for the transmitting tube for a signal/noise ratio loss of not more than 2 db. With the Lympne–St. Inglevert equipment a voltage variation of ± 3·5 per cent for the receiving or ± 4·5 per cent for the transmitting tube produces a

signal/noise loss of 6 db.   If the quenching oscillator of the Lympne–St. Inglevert equipment is stopped, so that reception is effected by something analogous to a reaction method, voltage variations of ± 1 per cent at the receiver or $1 \cdot 2$ per cent at the transmitter will give 6 db signal/noise ratio loss.   In these measurements the tests at the transmitter and at the receiver are made quite separately; i.e. if a change has been made at the transmitter no attempt is made to improve the circuit by readjustment of the receiver.   The percentage variation of the plate voltage depends upon the particular voltage used, since it is generally possible to find—within certain limits—a suitable grid voltage to match the plate voltage chosen.   In the case of the double-detection method a compensating circuit has been incorporated, so that any variation of supplies will produce compensating grid and anode variations.

The St. Margaret's–Escalles Link

The equipment used on the St. Margaret's–Escalles link is substantially the same as that already described for the Lympne–St. Inglevert link.   The mounting of the apparatus is, however, considerably different, as this equipment was intended for experimental work only.   In the experimental equipment the micro-ray tube has normally been located in front of the parabolic mirror, so that the transmission line from the tube lead-outs to the antenna is only a few centimetres long.

On the English side of the Channel the transmitting and receiving sets are situated on the cliffs about 1 mile north of St. Margaret's Bay.   The exact position is 1° 23′ 30″ E. longitude, and 51° 9′ 45″ N. latitude.   On the French side of the Channel the transmitting and receiving stations are situated at Cap Blanc Nez, which is about 13 km S.W. of Calais.   The exact position is 1° 43′ 20″ E. longitude, and 50° 55′ 30″ N. latitude. The apparatus on each side of the Channel is housed in two wooden huts about 80 yards apart.   At St. Margaret's the huts are about 80 yards from the edge of the cliffs, which at this point are 200 ft. high.   On the French side the transmitting and receiving stations are situated on high ground (450 ft. above sea-level), some 500 yards back from the edge of the cliffs.   The distance between the English and French stations is $22 \cdot 1$ miles, or $35 \cdot 7$ km. Each transmitting or receiving station employs a paraboloidal reflector whose aperture, 3 m in diameter, coincides with the focal plane.   The radiator is normally situated at the focus of the parabola, and a suitable hemispherical reflector may be located on the opposite side of the antenna to the main reflector.

As originally installed, the micro-ray tube was mounted in front of the paraboloidal mirror with a 2-cm doublet connected to the tube by a line 4 cm long.   It would be expected that with a small, straight antenna for transmitting the received radio waves would be plane-polarized.   This was not found to be the case.   The receiving antenna could be rotated through 90° in a vertical plane without changing the strength of the received tone.   This was probably due to the fact that at the transmitting station the doublet, connecting wires, and wires inside the tube, were all radiating.   The radiation was therefore not being emitted from a single, straight wire but from a number of wires arranged in ·

various directions.   When, however, a $\frac{1}{2}$-wavelength radiator and coaxial transmission line were used with the tube mounted behind the mirror, the received wave was plane-polarized as expected.   In this case rotating the receiving antenna through 90° in a vertical plane reduced the received tone by at least 40 db.

The careful choice of suitable sites for the two ends of an ultra-short-wave link is a matter of considerable importance.   In theory not only must it be possible to draw a straight line between the two ends of the link without passing through any intervening obstacles, but each site should be so chosen that the transmitted beams pass as high above the ground as possible.   Failing a site in free space, the practical ideal is one placed high up with the ground sloping down towards the distant station. It is worth noting that at the St. Margaret's end of the link the transmitting and receiving sites were somewhat different.   The centre of the beam from the transmitter cleared the top of the cliffs by only about 1 ft., whereas the centre of a beam transmitted from the receiving station would clear the top of the cliffs by about 14 ft. The two positions were compared by transmitting first from one position and then from the other.   During transmission from the receiving position the level of tone received at Escalles was 8 db higher than during transmission from the transmitting position.

(5) PROPAGATION

Observations have been made on the St. Margaret's–Escalles link during the periods February to June, 1931, May to December, 1933, May to August, 1934, and from May, 1935, to date (July, 1935).   The Lympne–St. Inglevert circuit now being in commercial operation, results for this link cover the period from January, 1934, to July, 1935, but normal operation is not continued long after sunset.   It will be noted that few winter experiments were made on the St. Margaret's–Escalles link.   This is on account of the difficulty of working in winter, the two stations—but more particularly the Escalles one—being in a very exposed position.   It may, however, be remarked that there have been very few recorded cases of appreciable fading on either link during the winter months, i.e. between the middle of November and the middle of April.   The Lympne–St. Inglevert observations have continued without interruption through the winter of 1934–35.   Observations have, during the above periods, been made for several hours each day during the morning and afternoon.   So far only a limited number—say 250 hours—have been made after dark, but up to the present no marked differences in fading conditions have been observed during day and night observations.   There seems, however, to be a tendency to less fading during the hours of darkness.

Profiles of the transmission paths of the two links are given in Figs. 16 and 17.

Atmospherics of the normal type were never heard on the circuit, though sharp clicks, which could not be traced to the apparatus itself, were sometimes noticed. No interference whatever was caused either by thunderstorms, even when within sight of the receiving station, or by the ignition systems of aircraft or motor-cars.   Except for the clicks occasionally heard the background noise in the receiver exactly resembled normal tube noise.

During work on the experimental link, it was observed that the received signal did not remain constant. The changes in field strength were comparatively slow and occurred practically simultaneously at the two terminals. Absolute values of field strength could not be measured, but from the level of the received tone a comparative value was obtained. A reaction type of receiver was used, so that no great accuracy can be claimed for the
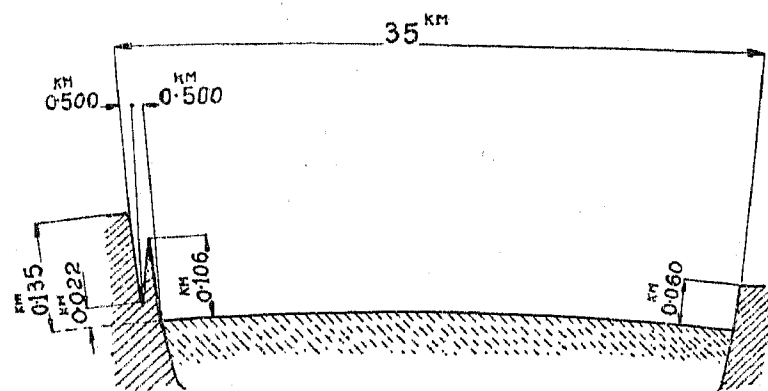

Fig. 16.—Profile of Escalles–St. Margaret's path.

measurements, and only changes in level in excess of 6 db were recorded.

The normal level of received tone was close to the maximum, that is to say the chief changes in field strength were in a downward direction. The signal seldom rose more than 6 db above the normal, though this may possibly be due to some overloading effect in the receiver. The maximum change in tone level which could be measured was about 40 db, changes equal to or greater than this value being recorded three times during the months of May and June, 1931. On three occasions of an average duration of 2 or 3 minutes the signal was uncommercial on telegraphy. Smaller changes of the order of 6 to 30 db occurred more frequently and were recorded 18 times during these 2 months. A detailed list of the variations, with dates and times, is given in Table 2.

It is probable that changes in field strength occurred more frequently than recorded. The radio circuit was in operation about 7 hours per day and 5 days per week, and during that time was being used for experiments,

During periods of low field strength attempts were made to improve the circuit by readjusting the receiver and transmitter and by rotating the transmitted beam

Table 2
PERIODS OF LOW FIELD STRENGTH, 20TH APRIL– 6TH JULY, 1931

Date	Start of period (B.S.T.)	End of period (B.S.T.)	Time of minimum signal (B.S.T.)	Level of minimum signal below normal
				db
23/4/31	18·00	—	18·30	40
1/5/31	15·00	15·30	15·10	12
1/5/31	18·00	18·43	18·26	40
7/5/31	11·00	12·45	12·00	15
15/5/31	15·00	15·08	15·20	12
15/5/31	18·15	18·30	18·20	15
18/5/31	—	11·00	9·30	40
18/5/31	—	15·40	15·30	10
21/5/31	—	15·00	14·45	10
22/5/31	18·20	18·32	18·27	15
27/5/31	12·20	12·37	12·31	18
28/5/31	9·35	10·00	9·45	13
28/5/31	11·17	11·33	11·30	9
28/5/31	11·45	12·15	11·58	22
9/6/31	—	11·00	10·26	40
9/6/31	16·10	18·40	18·15	11
16/6/31	16·30	—	17·00	26
17/6/31	11·40	15·20	—	20
22/6/31	16·30	18·30	17·13	26
23/6/31	11·30	12·30	12·12	28
23/6/31	15·38	16·09	16·00	13
29/6/31	12·30	16·20	15·22	30
6/7/31	10·40	11·47	11·34	40

through a small angle about a vertical axis. These attempts were rarely successful.

On two separate days in July, 1934, when reception with the paraboloidal mirror was weak (e.g. 20 db below normal) for about half-an-hour on end—this occurred
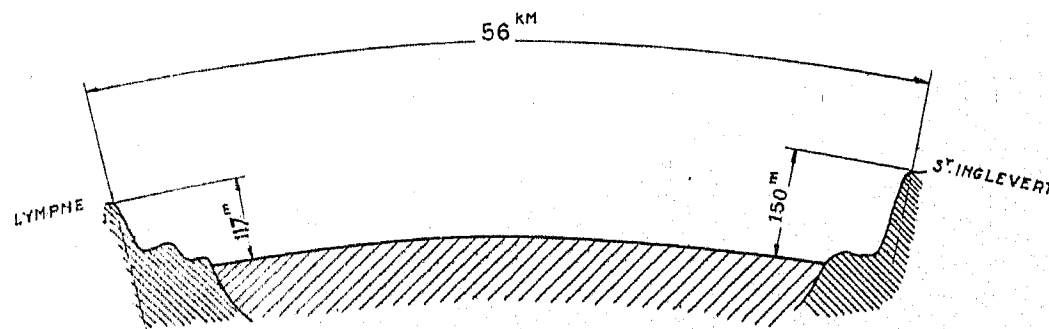
Fig. 17.—Profile of Lympne–St. Inglevert path.

some of which were of such a nature as to make it unlikely that a moderate change in field strength would be noticed.

It is important to note that during the Escalles–St. Margaret's observations of 1933 and 1934 a 6-metre ultra-short-wave link was established between the same points for comparison. No variation of received signal on this latter link was ever detected.

for about half-an-hour a day 5 days a week during the month of July, 1934—the spherical mirror in front of the transmitting paraboloidal reflector at Escalles was reversed so that the paraboloidal reflector was screened by the hemispherical mirror from the antenna. The received signal then increased by about 5 db. The experiment was repeated several times in the course of the half-hour period and the same result obtained. The

conclusion would at first sight appear to be that the beam from the paraboloidal reflector was deflected from its normal course and that an increase of signal was received at the receiving station when the beam had been rendered much wider. It should, however, be remarked that this conclusion is not entirely free from doubt, since any change to the reflectors near the transmitting antenna causes a change of impedance in that antenna with a consequent reaction upon the micro-ray tube itself, and to check up the adjustments of the transmitter is an operation which with the experimental equipment required several minutes. In other words, if the transmitter was slightly off tune it may have been brought back into tune by this operation. It is, however, not likely that the transmitter was off tune on the two occasions that this experiment was made. It must not be forgotten that, owing to diffraction around the edges of the hemispherical mirror, the paraboloidal reflector is not put entirely out of service by the simple manœuvre of reversing the hemispherical mirror. Nevertheless, this experiment gives grounds for believing that the beam had been deflected out of its normal path, since reversing the hemispherical mirror certainly reduces the directivity of the system.

In order to check further whether the beam was deflected from its normal course, experiments were carried out with the echelon grating already described. On three occasions, when fading was bad, the transmitting echelon grating at Escalles was rotated about a vertical axis. It was found that the beam had to be directed 1° off its normal course in order to give a maximum signal at the receiver. This maximum signal was 6 db stronger than the signal received under these fading conditions, with the normal orientation of the grating, which could be rotated through an angle of ± 3°.

Unfortunately it was not possible to rotate the aerial systems about a horizontal axis at the same location, but facilities for this experiment were provided at the St. Inglevert transmitting station. During fading in the early months of 1934, repeated attempts were made on several occasions to increase the signal by rotation of the aerial system about a horizontal axis; no such increase in signal was ever obtained or apparent change of beam direction observed, although the aerial system was rotated through an angle of ± 10°.

The periods of low field strength lasted from 10 minutes to 2 hours and occurred at all times of the day. The results indicate that the field is more likely to be unsteady on bright, still days than on dull and windy days, but the question is rather complicated by the fact that the weather conditions are frequently not uniform over the whole length of the circuit. If the transmitted beam is bent in a manner similar to the refraction of light, then the temperature gradient in the atmosphere along the transmission path may play an important part in signal-strength variation. Rain and fog were not found to have any effect on the circuit.

The transmitters on the St. Margaret's–Escalles experimental circuit were placed so that the centre of the transmitting reflector system was about 8 ft. from the ground. It was thought that the distance of the transmitter from the ground would have a considerable influence on the strength of the received signal, and it was expected that the signal at the distant receiving station would probably increase as the transmitter was raised above the ground. Preliminary tests were made at St. Margaret's by simply raising and lowering a transmitting tube and antenna without a reflector system. In order to do this a wooden support was fixed to the back of the transmitting mirror shed so as to project about 6 ft. above the mirror shed roof. The transmitting tube was mounted on a wooden base and was raised by means of a cord passing over a pulley fixed to a wooden arm projecting 6 ft. from the side of the mirror shed and fixed to the wooden support referred to above. The necessary power was led to the tube through two pairs of twisted flex. With this apparatus it was found possible to carry on a 2-way telephone communication with Escalles under favourable conditions; the signal level at Escalles was, however, between 20 and 30 db below that of the normal circuit. It was found that, as the transmitter was raised from zero to a height of 20 ft. above the ground, the strength of the received tone at Escalles went through a series of maxima and minima. The maxima occurred at 3 ft., 8 ft. 6 in., 13 ft., and 20 ft.; the last may not be a true maximum, since this was the greatest height to which the tube could be raised. Minima occurred at heights below 1 ft., and at 5 ft., 10 ft. 6 in., and 18 ft. There was, however, no great change in signal strength between 11 and 20 ft. The maximum at 8 ft. 6 in. was very marked and the received tone at this height was about 10 db above the tone received when the transmitter was at a height of 20 ft. There seemed to be a very rapid fall in signal strength between 9 and 10 ft. The signal being at all times weak, it was extremely difficult to obtain measurements of the relative signal strengths for different transmitter heights.

The optimum height, 8 ft. 6 in., coincides with the height of the centre of the transmitting paraboloidal reflector. This fact at once suggests that the transmitter, mounted as described, was in some way influenced by the proximity of the transmitting reflector system. It is not at all clear how the reflector system was operating during this experiment, since the transmitter was mounted about 8 ft. to the side and some 2 ft. behind the back of the paraboloidal reflector. In order definitely to settle this point, it would be necessary to carry out further experiments with the transmitter located some distance from all objects likely to cause interference; lack of time prevented the carrying-out of this experiment.

In the case of both the St. Margaret's–Escalles and the Lympne–St. Inglevert links the wavelengths used have been almost identically the same in both directions. It has been observed that fading in these circumstances is practically simultaneous in both directions and that it is unaffected by a change in the polarization of the waves used.

How is this fading to be explained? It has been seen that it cannot be a simple deflection of the beam since rotation of the antenna system usually fails to recover any part of the signal. Schelleng, Burrows, and Ferrell,[*] and also Trevor and Carter, have suggested that, on ultra-short waves of the order of 3 to 5 metres,

* See Bibliography.

a signal at the receiving station is the resultant of the field strengths of two rays, one travelling by a direct path from the transmitter to the receiver and the other suffering reflection at the surface of the intervening terrain. As the reflected ray undergoes a phase change of substantially 180° at reflection, the field strengths of the two interfering rays will be substantially equal and opposite if the difference in path length is an integral multiple of the wavelength, while they will be in phase if the difference in path length is an odd multiple of $\frac{1}{2}$ wavelength.

Since the refractive index of the atmosphere is, in general, a function of the height above sea-level, neither the direct nor the reflected ray travels in a straight line. The length of the path is therefore dependent on the variation of the refractive index of the atmosphere. It is possible to calculate the clearance at the point of reflection between the direct- and reflected-ray paths for any given condition of variation of the refractive index of the atmosphere. It has been shown by Dr. Eccles that when the dielectric constant varies as a function of the height above sea-level only, the path of the ray can be determined by treating the earth as though its radius had been changed and the atmosphere had become

Table 3

Condition		Equivalent radius	Effective clearance	
			Low tide	High tide
		km	m	m
Summer, average	..	8 650	69	61
Summer, dry ..	..	7 950	65	57
Winter, average	..	8 420	67	59
Winter, dry ..	..	8 100	66	58

homogeneous. The average equivalent radii are given by Schelleng, Burrows, and Ferrell.* From these figures, the clearance, and consequently the difference in path length, have been calculated for the case of the Lympne–St. Inglevert link. Fig. 18 shows the computed relative signal strength of wavelengths of 15 cm, 17·5 cm, 20 cm, and 29 cm, for different values of clearance between the direct- and reflected-ray paths. Table 3 gives the effective clearance for summer and winter, under dry and average conditions.

It will be seen from Fig. 18 that the winter range of clearance variation will involve relative variations of signal of approximately 9 db on 17·5 cm, whereas the summer range of clearance variation will give on the same wavelength approximately 15 db. It can be seen, however, that the signal is rapidly approaching its lowest value, so that it will be expected from these considerations that fading conditions would be much worse in summer than in winter.

The above argument has been based on the assumption that the refractive index of the atmosphere is constant at any given height above sea-level. This, however, can hardly be expected always to be the case, since there are almost always temperature and pressure differences

* *Proceedings of the Institute of Radio Engineers*, 1933, vol. 21, p. 458.

between Lympne and St. Inglevert. During winter the sky is generally obscured, there is usually a wind of fair strength, and temperature-differences between land and sea are not pronounced. During summer, however, there may be abrupt changes of temperature, pressure, and humidity, along the path of the rays, particularly at the coast lines. Thus the winter range of clearances shown in Fig. 18 gives a reasonably accurate idea of propagation conditions during the winter, but the summer range of clearances, even though the picture is much more favourable than must be expected in practice, shows that propagation conditions in summer would be much less stable than in winter.

During summer it must be expected that the signal will be affected by interference between direct and reflected rays, whose path lengths may be varied considerably by non-homogeneity of the atmosphere, that more than one reflected ray may be encountered due to reflection at surfaces of abrupt refractive-index change, and that power may be lost in both the direct and reflected rays due to reflection back towards the transmitter of rays incident on a surface of abrupt refractive-index change. Absorption need not be considered, since experience shows that the normal strong signal may be received under all conditions of temperature, pressure, humidity, fog, rain, hail, or snow.

Inspection of Fig. 18 suggests that fading on wavelengths of 17·5 and 19·4 cm would, in general, be different; for clearances less than 70 m fading should be in the same sense, while for clearances between 70 and 74 m fading will be in opposite senses. Fig. 19 represents the working signal current operating the teleprinter at Lympne on 17·4 cm and at St. Inglevert on 19·4 cm on the 18th, 19th, and 20th July, 1934. Although these relative signal currents cannot easily be expressed in terms of decibels variation, they serve to show that on the 18th July, 1934, fading on the two wavelengths considered was usually in opposite senses. On the 20th July, 1934, however, it will be seen that fading was almost always in the same sense. The fact that observations in one case were made at St. Inglevert and in the other case at Lympne is immaterial, since experience has shown that fading at Lympne is always the same as fading at St. Inglevert, provided the same wavelength is used in both directions. The 19th July, 1934, was a day of violent fading on both wavelengths, but it will be observed that in no case do the two wavelengths suffer deep fading simultaneously. This is what might be forecast from inspection of Fig. 20 (A, B, and C). The probability of simultaneous deep fading on any two wavelengths decreases, as the number of reflected rays increases.

Inasmuch as the amplitude of the received signal is dependent on an interference pattern, variation of this pattern at audio frequency would cause a corresponding noise in the receiver. Such a rumble has been heard on several occasions. On the 18th July, 1934, it was heard at St. Inglevert after dark but was not observed at Lympne. On the following day it was heard at both St. Inglevert and Lympne during the afternoon and after dark. It persisted for periods of $\frac{1}{4}$ hour on end and recurred at intervals of 1 to 2 hours. The phenomenon introduced no loss of signal strength but caused some
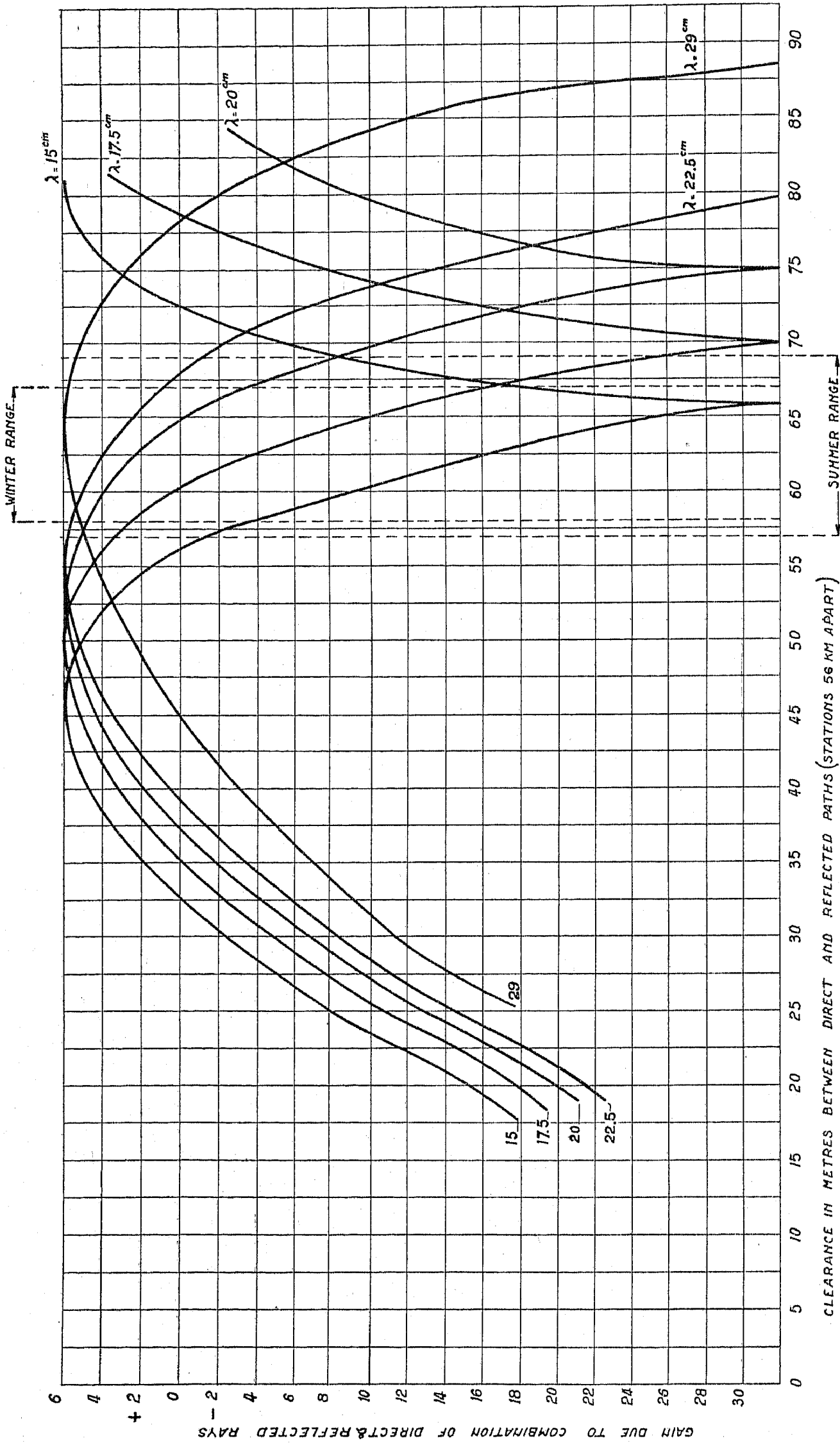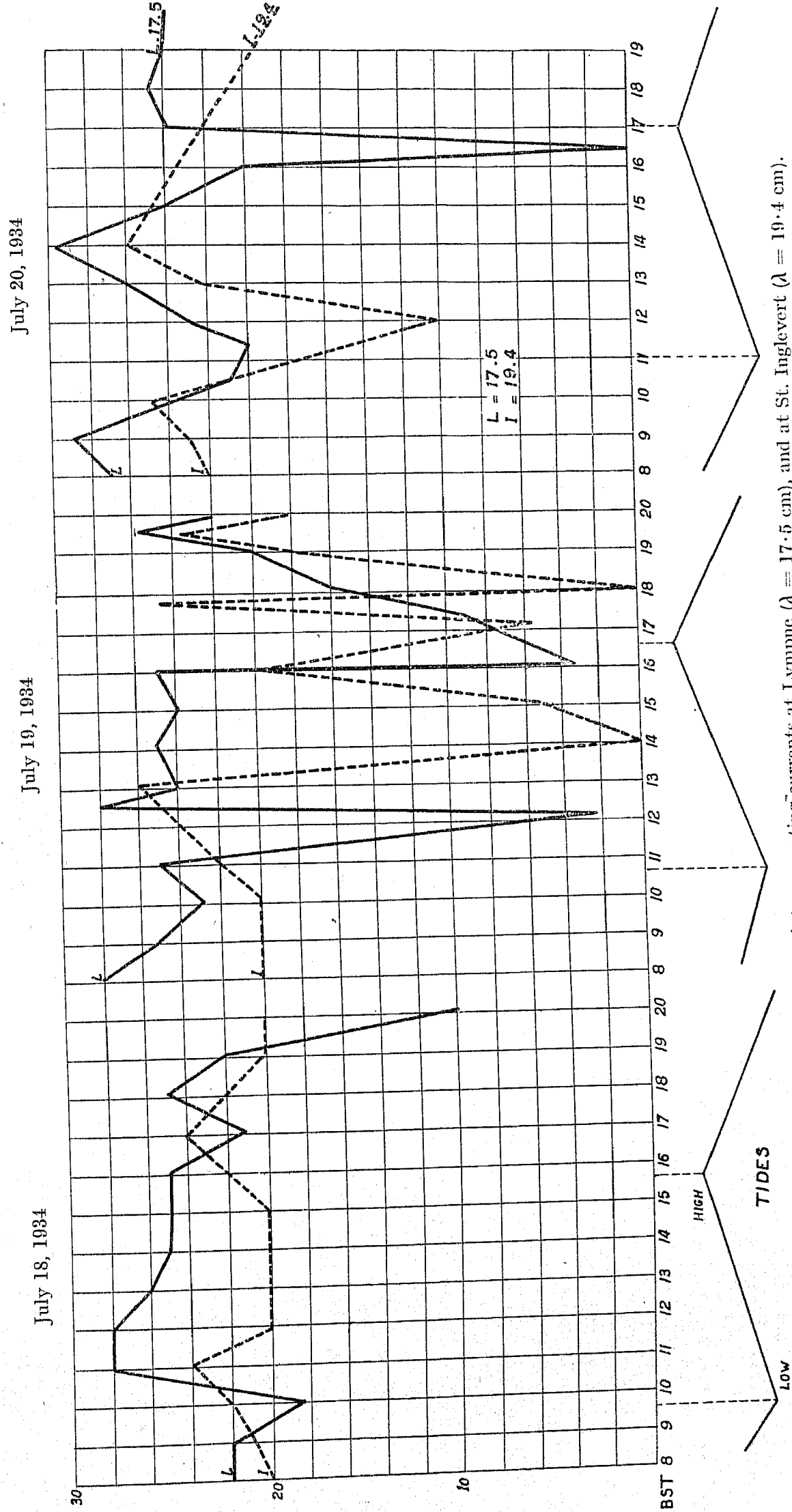
Fig. 18

Fig. 19.—Simultaneous observations of teleprinter operating currents at Lympne ($\lambda = 17 \cdot 5$ cm), and at St. Inglevert ($\lambda = 19 \cdot 4$ cm).
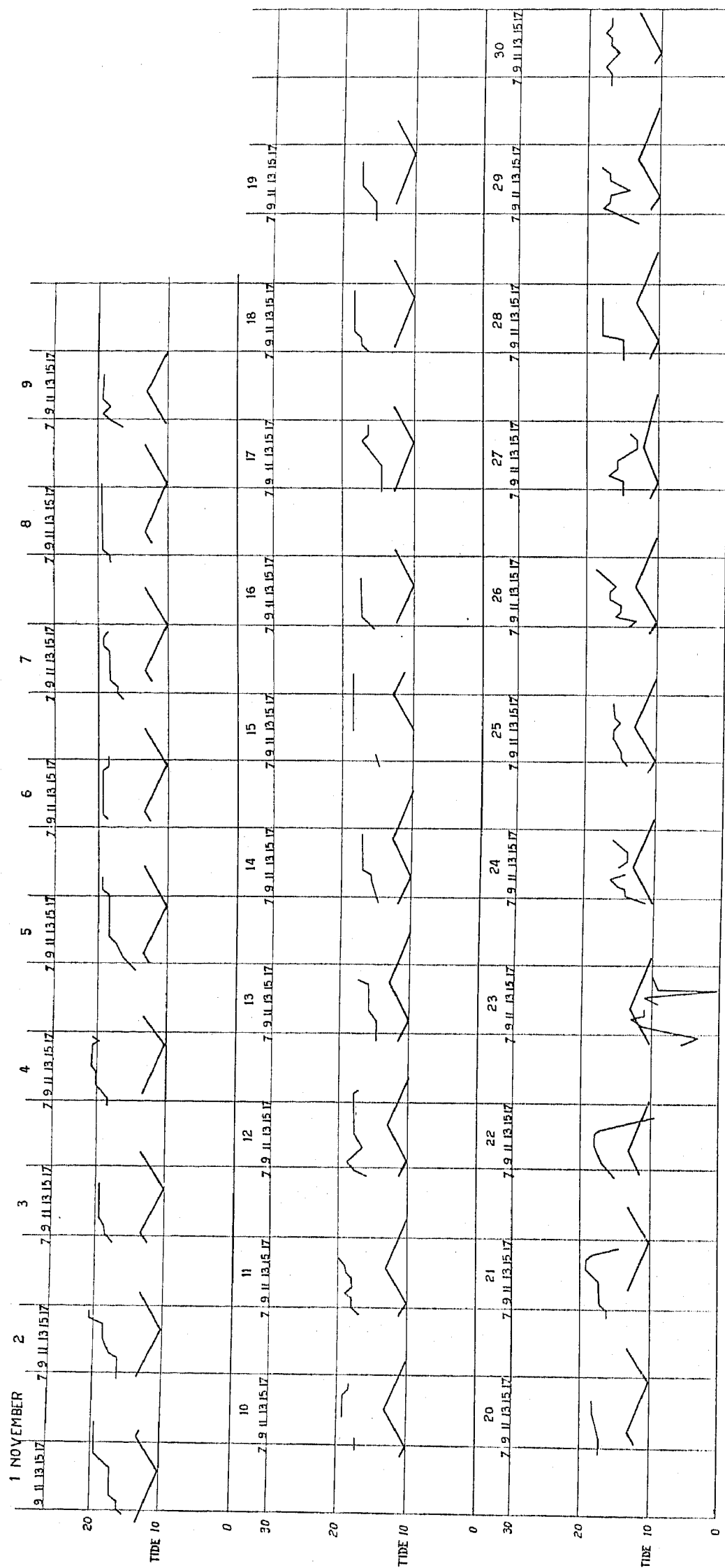
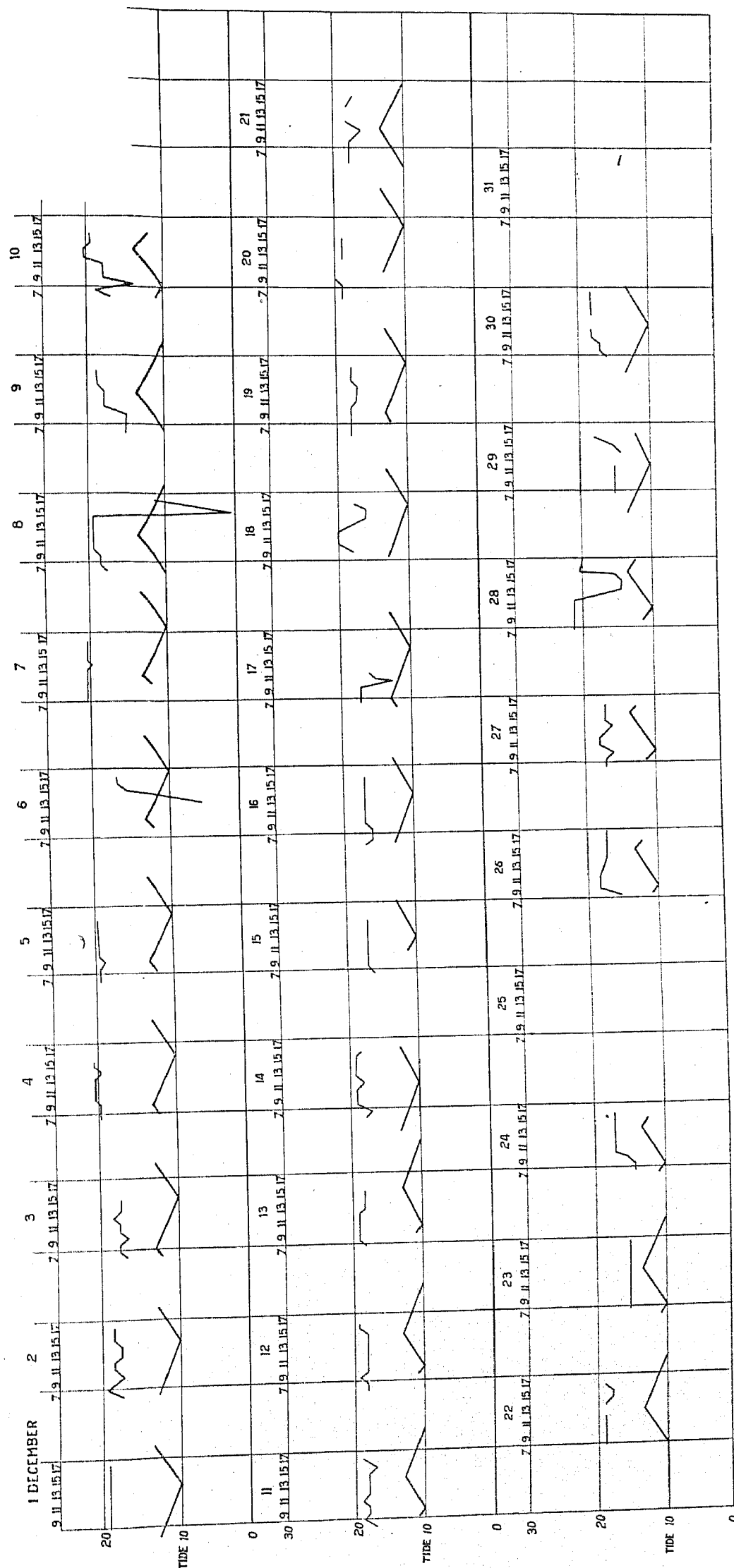Fig. 20A.—Micro-ray signal variation at Lympne, November, 1934.

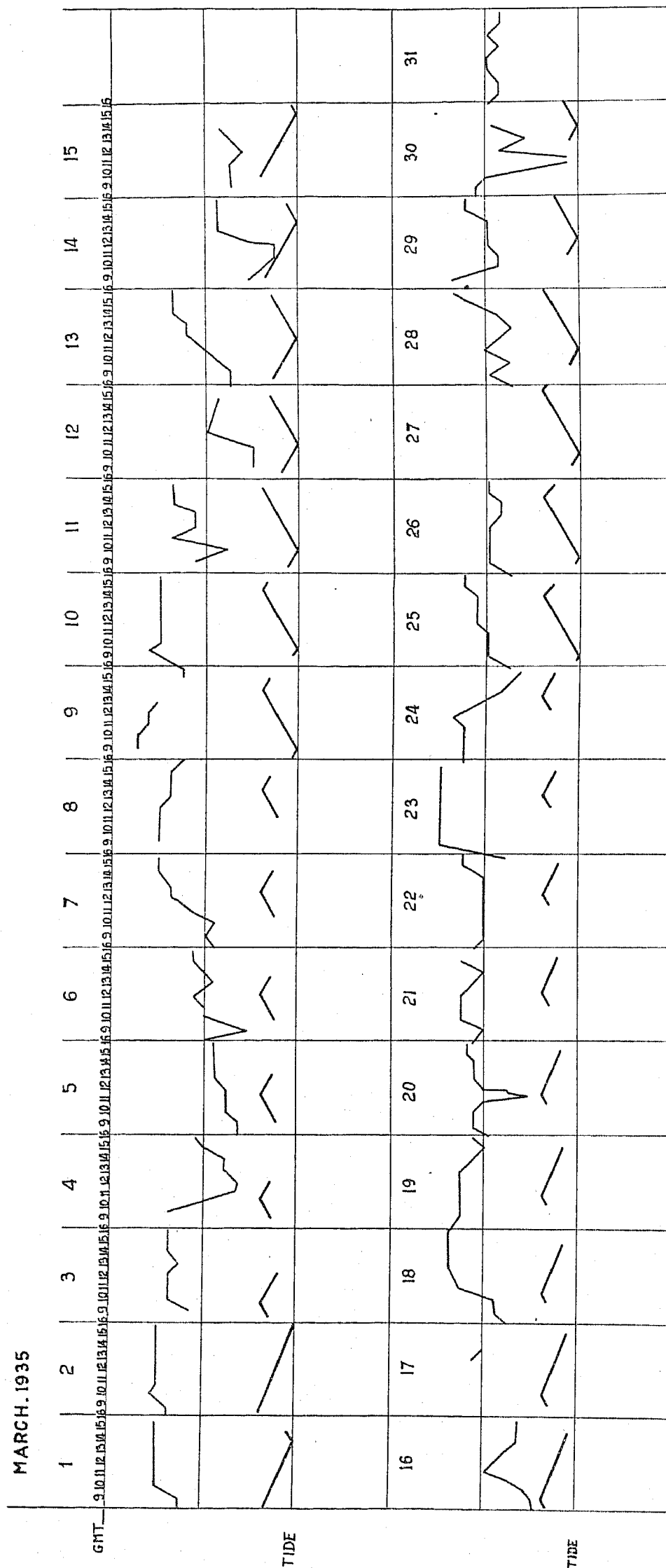Fig. 20B.—Micro-ray signal variation at Lympne, December, 1934.

Fig. 20c.—Micro-ray field strength of Lympne wireless telegraph station, March, 1935.

distortion with consequent reduction of intelligibility. It did not seriously impair the signal/noise ratio.

As there is a variation of as much as 8 metres between high and low water halfway across the Channel, it would be expected from the two-wave theory that the effects of the tides on the micro-ray signal would sometimes be noticed. In order, however, that this effect shall not be masked by other factors, atmospheric conditions must . be stable over the whole path during the period of observation, so that the phenomenon would be looked for in winter rather than summer records. It would be expected that the turn of the tide would cause a change in the rate of rise or fall of signal when the latter is not constant, but not necessarily that it would produce fading when the signal would otherwise be steady, since for certain values of path difference between direct and reflected ray the rate of change of signal with path difference is zero.

Figs. 20A, 20B, and 20C give a daily record of the working signal current operating the teleprinter at Lympne on 17·4 cm and also the state of the tides for the months of November and December, 1934, and March, 1935. The times of high and low tide plotted relate to Boulogne-sur-Mer. High and low tide at Lympne occur about $\frac{1}{4}$ hour later, so that the turn of the tide at the centre of the path is approximately 7 or 8 minutes after the times plotted. Although the effect of the tides is masked in many instances by other fading causes, it seems to be rather definitely suggested by the records of the six days from the 25th to the 30th November, 1934. In nine cases out of ten the turn of the tide during this period is seen to be accompanied by a marked change in the slope of the signal-current curve. During March, 1935, such marked changes occurred 16 times, the signal was constant 10 times, and fading continued without substantial alteration twice. The hypothesis that there exists interference due to the indirect ray reflected at the sea surface receives strong corroboration.

It will be noted that on some occasions the signal was constant during the turn of the tide but increased appreciably some hours later. If the field strength at the receiver is the vector sum of two substantially equal rays, the rate of change of signal with path length must have been zero at the tide turn, so that the signal should then have been a maximum or a minimum. It clearly was not the latter, as the minimum would be around zero. Rejecting the possibility of absorption for reasons already given, we are driven to one or more of the following conclusions:—

(1) There is varying attenuation of rays due to non-homogeneity of the transmitting medium.

(2) There is sometimes more than one indirect ray present.

(3) The beam is sometimes deflected from its normal course. This involves the three-dimensional directive diagram of the transmitting and receiving aerial systems.

In order to measure the directivity, the reflector system at Escalles was mounted in such a manner that the reflector and antenna system could be rotated about a vertical axis. As the transmitting antenna system at Escalles was rotated, the relative strength of the received signals was measured at the distant receiver at Dover.

The directive curves were taken using at the transmitter a concentric tube type of transmission line and a half-wave antenna; no spherical mirror was used. The results indicate that the directivity in a horizontal plane is greater when using a vertical antenna than when using a horizontal antenna. This is what would be expected from considerations already set forth when the theory of the paraboloidal mirror was treated. Directive curves taken on different days and at different times of day do not agree. The results indicate that during periods of low field strength the directive curve is sharper than at periods of normal or high field strength. This fact seems to indicate that the beam may at times be deflected in a vertical plane and that it is this deflection of the beam which gives rise to the variations in width of the received beam.

The results obtained during periods of normal field strength may be set out as in Table 4.

The echelon grating was so mounted that it could be rotated about both a horizontal and a vertical axis. When tilted about a horizontal axis the received tone was

Table 4

ANGLE THROUGH WHICH TRANSMITTING REFLECTOR SYSTEM MAY BE ROTATED ABOUT A VERTICAL AXIS FOR 10 DECIBELS LOSS

Reflector system	Antenna	Level of tone compared with maximum	Degrees from maximum
		db	
Paraboloidal ..	Horizontal	− 10	3·7
Paraboloidal ..	Vertical	− 10	2·2
Echelon grating	Vertical	− 10	2·5

9 db down for a 3° tilt and 13 db down for a 3·5° tilt; these tests were made when using a vertical antenna.

The paraboloidal system at Escalles was rotated through a large angle for the purpose of discovering " ears " on the directive curve. Reception was effected at St. Margaret's. The signal disappeared entirely at ± 8°, and three " ears " on either side were found for a rotation up to 40°. The signals due to these ears were far too weak to measure, being only just audible. They may be due partially to surrounding objects, since it was not possible to discover " ears " on the Lympne transmitting antenna system.

The diameter of the paraboloidal reflector was 3 m and of the echelon grating 4 m.

The gain of the echelon grating with spherical mirror was measured as 17 db greater than that of the grating with spherical mirror reversed so as to prevent rays from the antenna from reaching the grating. The paraboloidal receiving reflector at St. Margaret's gives a gain of 25 db. Both these results apply to times of normal propagation.

Simultaneous observations have been made at Lympne of micro-ray signal strength and temperature, pressure, and humidity of the atmosphere. Figs. 21A and 21B show these records for 5 days in June and 5 in July, 1934. The signal is shown in terms of teleprinter current in milliamperes. The times of high tide and low tide
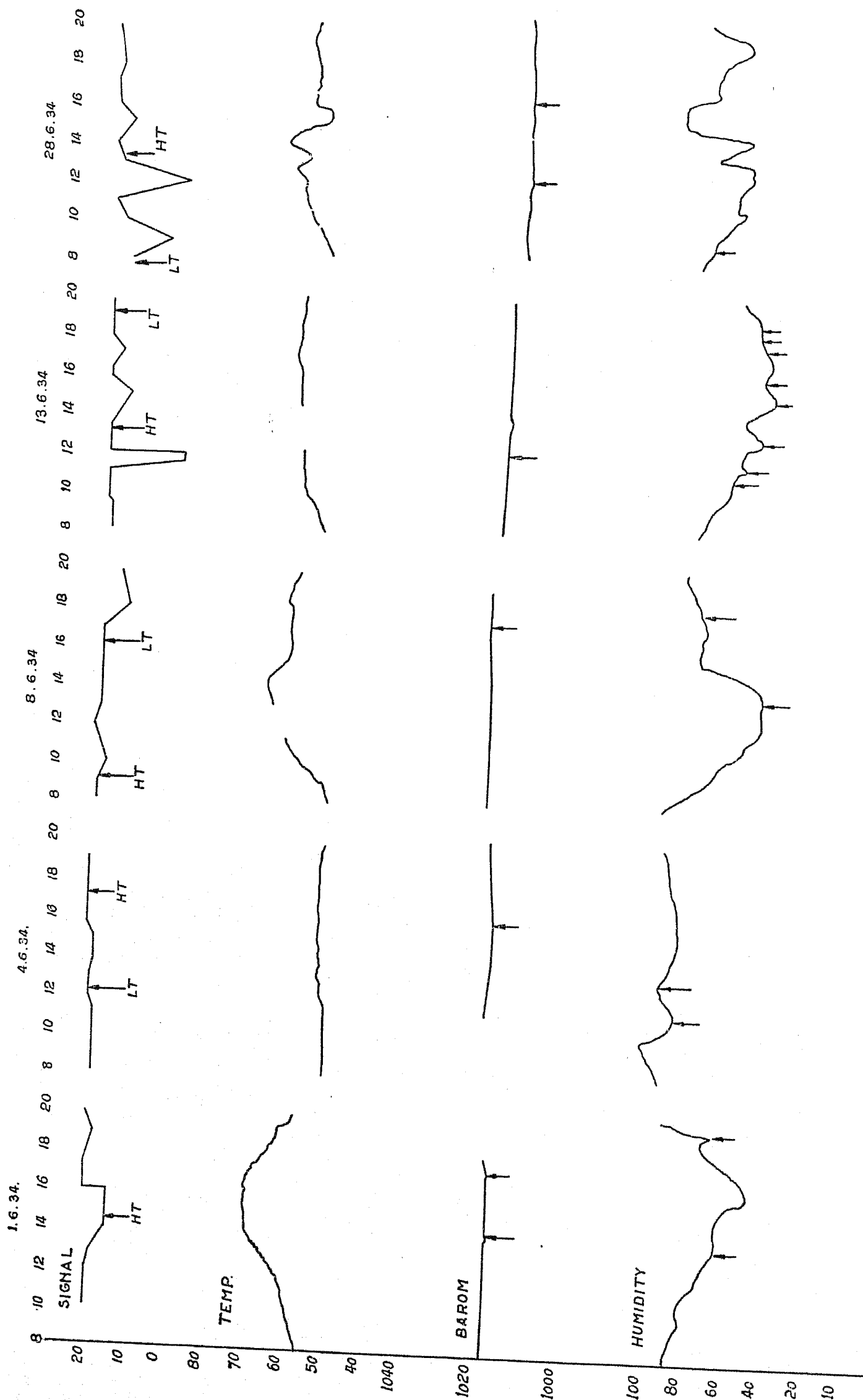
Fig. 21A.—Variations of signal strength, temperature, pressure, and humidity, June, 1934.
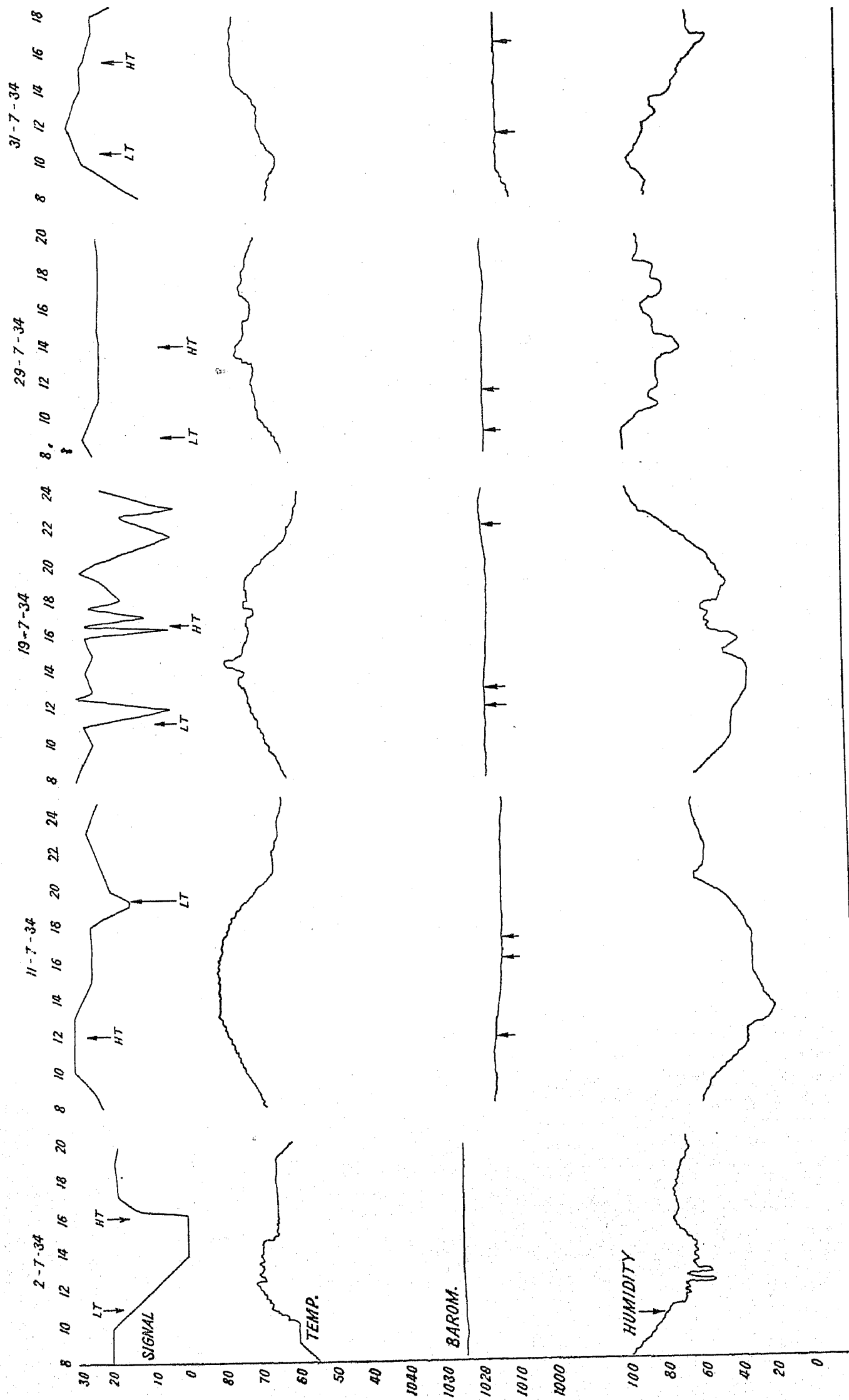HT = high tide; LT = low tide.

Fig. 21B.—Variations of signal strength, temperature, pressure, and humidity, July, 1934.

HT = high tide; LT = low tide.

have been marked by the letters HT and LT respectively. An arrow means that the record showed a small but abrupt variation. If the atmosphere along the transmission path is not homogeneous, it might be expected that the beam would be deflected from the normal path. Unfortunately it is not convenient to make temperature and other observations along the path itself, but it may reasonably be assumed that irregularities in any one or more of the three meteorological characteristics plotted against time at any one location will generally be accompanied by similar irregularities in these characteristics plotted against distance at any one time. It will be seen from Figs. 21(a) and 21(b) that barometric variations were too small to be recorded; unfortunately micro-barograph records were not available. In general, the temperature and humidity curves move, as might be expected, in opposite directions; that is to say, when the temperature rises the humidity falls. The rapid variations of both temperature and humidity on the 2nd July and of humidity between 16 and 18 o'clock on the 19th July would appear to indicate non-homogeneity of the atmosphere. It will be noted that on these days considerable fading took place. Similarly the abrupt variations of humidity on the 13th June would also lead us to expect considerable fading, and we see that the signal disappeared almost entirely just before noon. · Similar remarks apply to the 26th June. On the other hand, a steady signal is accompanied by absence of abrupt changes in temperature and humidity. In reading these figures it must be borne in mind that, when variations of humidity follow very closely the temperature variations but with opposite sign, the transmission path probably remained homogeneous.

The general conclusion to be drawn is that the primary condition for good micro-ray working is a thoroughly well-mixed and homogeneous atmosphere, free from "pockets." In the summer, currents of hot air probably create "pockets" of very different refractive power from the rest of the atmosphere and the direction of transmission may be violently changed and/or unusual attenuation introduced. In summer the passage of a cloud across the sun's rays will give a temperature kick of magnitude different above the land from what it is above the sea, owing to the difference in re-radiation from land and sea. We may, then, consider the transmission path as being through a compound lens of at least three elements of different densities. Add an air "pocket" and the problem becomes one of a compound lens with a bubble in it.

If we admit that there is a reflected ray, clearly its path will be subject to the same type of perturbation as already mentioned but possibly not at the same time or of the same magnitude as for the direct ray. This makes the problem exceedingly complex.

The path of the St. Margaret's–Escalles link is apparently simpler, as it is nearly all over sea. At cliff faces, however, strong currents of hot air often arise; this would introduce the compound-lens idea at once. There is also the possibility of diffraction at the cliff edge.

The results of experience of the two links described may be summarized as follows:—

(1) The most stable micro-ray conditions coincide with very stable atmospheric conditions as judged by thermometer and barometer.

(2) Given stability of temperature and pressure, the actual values seem to have no importance.

(3) Given stable temperature and pressure, rain, hail, snow, or fog, do not affect the link.

(4) No definite relation between the electrical state of the atmosphere (potential gradient) and micro-ray stability has been found. Excellent operation has been obtained during thundery periods, but there is no information as to the general atmospheric stability at the time.

(5) A high wind is almost invariably accompanied by good micro-ray transmission.

(6) Sudden changes in temperature are usually accompanied by micro-ray fading; likewise sudden barometric changes. Rapid fluctuations in temperature occur much more frequently on hot days than on cold days; fading is much more pronounced during the summer months than in winter.

(7) The settling of a heavy bank of fog has been accompanied by very severe and rapid fading, followed by stability when the fog bank has ceased to move.

(8) During summer extremely violent fades of very short duration—1 to 2 minutes—have been noticed.

(9) During summer fading at audio frequency seems to occur both in broad daylight and in darkness.

(10) Ultra-short waves of 6 m length are much stabler than micro-rays over optical paths across the Straits of Dover.

(11) In noisy locations micro-rays have the advantage over ultra-short waves of being much less affected by "man-made static."

(12) Micro-ray communication is much more private than ultra-short waves.

(6) GENERAL

The term "micro-rays" is generally understood as covering the band of wavelengths from the lower limit of, say, 1 cm up to a maximum of 100 cm, while the range between 100 cm and 10 m is usually referred to as the "ultra-short-wave" band. These are, of course, purely arbitrary divisions and no sharp boundary line can be drawn. The micro-ray band would in fact seem to mark a transition stage in which it would probably be justifiable to include the wavelengths of 50–100 cm as ultra-short waves, inasmuch as mechanical considerations necessitate the use of aerial systems along the lines developed in that connection and embodying reflecting elements composed of oscillating dipoles of definite lengths determined by the wavelength in use. Below 50 cm, however, it becomes more and more feasible to make use of aerial systems embodying the principles of optical technique, more especially the use of aperiodic metallic reflectors instead of reflecting dipoles. Keeping these considerations in mind we may, then, regard micro-ray communication as being the limiting case of the fairly well-explored short-wave and ultra-short-wave groups and the beginning of a new, and as yet almost entirely unexplored, region of the frequency spectrum.

The particular feature of micro-ray technique which stands out is the sharp three-dimensional directivity which is made possible by the use of reflecting systems

designed according to the laws of optics. It has been shown elsewhere in the paper that an extremely useful degree of concentration can be attained with the aid of a paraboloidal mirror reflector having an aperture of only 18 wavelengths, such a reflector giving a gain of approximately 28 db and a plane angle of radiation of about $\pm 3°$. On the wavelengths around 18 cm on which most of the experimental work with this type of reflector has been done, such an aperture is approximately 10 ft. in diameter. While this is very small in comparison with the aerial dimensions usually required even on the ordinary short wavelengths, it is so large as to be rather unwieldy and to involve serious mechanical problems of transport and erection. With still shorter wavelengths, however, these problems would rapidly become negligible, and on wavelengths of about 5 cm it is possible to visualize an equipment of a reasonably portable nature and of very high directivity which might be of the greatest importance in certain military situations.

The question now arises as to what extent we can make use of the sharp directivity which is possible by such application of optical principles, bearing in mind that they are made possible only by the efficiency with which micro-rays can be reflected. Given an absolutely constant propagation path free from obstacles, it is obvious that no difficulty arises. If, however, the propagation path varies for any reason, a limit is at once set to the extent to which the directional properties can be utilized. Moreover, it is necessary to take into account not merely the direct propagation path, but also any indirect path by reflection such as might occur when the edge of the beam touches the earth, in which case an interference pattern is set up in the field round the receiving station. If this interference pattern is constant, it is only necessary to find a suitable location for the receiving aerial assembly; but a rather different situation arises if the length of either or both of the direct and reflected paths is liable to change, as we then get a shifting interference pattern which, in combination with a receiving aerial fixed in space, gives rise to fading of the same type as is encountered in the short and medium wave-bands. In such a case it would apparently be necessary either to use simultaneously more than one wavelength or to have recourse to a diversity reception scheme using a number of receiving aerial systems spaced so as to give a signal which remains substantially constant no matter how the interference pattern may be located.

In view of this consideration we might perhaps divide the field of exploitation into two parts. The first would cover relatively short ranges giving unobstructed propagation path for the direct ray and an indirect ray of intensity greatly reduced by means of the directional polar diagram at the transmitter. Over such ranges the variations in the direct propagation path would normally be only of small magnitude and the system would operate so as to give a consistently strong signal free from fading. The second part would comprise systems operating over longer distances in which interference due to any reflected ray was of appreciable importance. As shown in the section on propagation, such a system might, according to the value of certain meteorological variables, give an almost stationary interference pattern and a reasonably uniform signal when using only one receiving aerial; alternatively the interference pattern might be very variable and necessitate diversity reception in order to obtain consistent performance. In both cases the system would be characterized by, it is believed, an entire absence of atmospherics and interference from ignition systems, etc.

So far we have considered only propagation and directional effects. It is, however, a feature of micro-ray operation that it lends itself to the use of extremely large band-widths. The immediate possibilities of this feature include multi-channel working and television with its associates, picture and facsimile transmission. It is as yet rather early to say just what applications would be involved. Where, however, it is a case of making a temporary link for television purposes, there is little doubt that micro-ray circuits could be usefully employed.

As viewed from the military standpoint, micro-ray working, particularly at the very short-wave end of the band, presents rather important possibilities. By virtue of the very high directivity which is possible, combined perhaps with some addition of selectivity by rotation of the plane of polarization, it would be possible to operate simultaneously over a comparatively small area large numbers of micro-ray channels which would have the peculiar advantage of being, for most practical purposes, entirely secret. It is questionable whether such a scheme of communication could readily be jammed. Quite apart from any military use, the degree of secrecy inherent in micro-ray work with its special valves, etc., might be a determining factor in the choice of a communication system for bridging natural obstacles which would otherwise interrupt the linking of important commercial networks. It will, of course, be understood that, in addition to the special features which render micro-ray reception by the general public improbable, privacy systems as developed for short-wave and long-wave radio may equally well be applied to micro-rays.

Given the possibility of using highly directive aerials, their application to beacon purposes inevitably arises. The small dimensions of the aerial and reflector assemblies required for micro-ray working obviously suggest rotating beacons operated in the same manner as those installed at Orfordness and Inchkeith (in the Firth of Forth) working on medium and ultra-short waves respectively. The fact that a wide frequency band is available free from interference renders feasible such installations in numbers and location density as could not be contemplated were we restricted to more normal wave-bands. Nor is it necessary to limit the field to the rotating beacon. An ingenious type of oscillating beacon designed for homing purposes was demonstrated off the coast of Italy in June, 1934, by the Marconi Co., and there is no reason to believe that the orthodox type of two-tone homing beacon used on American aeroplane routes could not be made to function equally well on micro-ray wavelengths. In the meantime the commercial use of micro-rays for direction-finding purposes is handicapped by the lack of experience of wireless operators with this type of equipment.

The exploitation of micro-ray communication systems

by aircraft offers an attractive but rather tantalizing field. Assuming that aircraft restrict themselves to omnidirectional reception, the extremely small size of aerial is at once recognized as a marked advantage. The location of this aerial, however, may involve unexpected difficulties, due to the requirement that it must not be screened by any part of the aeroplane structure in the direction from which signals are expected, while care must also be taken as to possible reflections from wing and body surfaces, the effect of such reflections varying with the angle of incidence of the received signal. As the majority of external surfaces in aircraft are nowadays either metallic or largely metallized by aluminium paint, the problem is no small one. If these difficulties are overcome, an enormous easement of the aircraft communication problem will immediately be felt, and interplane working and beacon-guided landing and homing can be contemplated without fear of the present bugbear of ether congestion. So far as is known, no experience is yet available by which the value of the micro-ray band of wavelengths for aircraft communication can be gauged with any degree of reliability.

The possible use of micro-rays in therapeutics is as yet a wholly unexplored field, largely on account of the smallness of the power which can conveniently be generated and the rather critical nature of the necessary adjustments. Experience has shown that it is decidedly dangerous to dogmatize as regards either radio or medicine, and from prophesying as to the combination onê is inclined to draw back as from a bottomless abyss. The most that can be said at the present time—and it must be taken as a pious opinion rather than as an article of faith—is that from the standpoint of ordinary tissue heating the use of micro-rays would appear to offer some advantage over 6-m to 15-m oscillations in depth of penetration. Whether with particular frequencies selective absorption would occur in any particular kind or location of tissue it is absolutely impossible to say, and the effects of such selective absorption, assuming that it did occur, are equally unpredictable. It seems probable that the special biological effects, which cannot be accounted for on a purely thermal basis but which are generally admitted to occur with oscillations of wavelength below 6 m, would become prominent with centimetre waves. It is to be hoped that, before charlatans enter the field, the trained medical profession will be able to give some authoritative judgment as to the value or otherwise of " micro-ray treatment."

ACKNOWLEDGMENTS

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Abridged Chronological List of Investigations on Short and Ultra-Short Waves

Author	Year	Wavelength
		cm
Valve Oscillators of Normal Type		
White	1916	600
Gutton and Touly	1919	200–400
Van der Pol	1919	375
Southworth	1920	110–260
Holborn	1921	300
Mesny	1924	100–500
Gutton and Pierret	1925	50–200
Kruse	1927	41–600
Englund	1927	100–500
Yagi	1928	60–200
Bergmann	1928	80
Ritz	1928	300
Esau and Hahnemann	1930	300
Brown	1930	200
"Barkhausen and Kurz" Oscillators		
Barkhausen and Kurz	1920	43–200
Gill and Morrell	1922	200–500
Scheibe	1924	30–330
Grechowa	1926	18
Hollmann	1928	20–140
Uda	1930	50
Beauvais	1930	15–18
Potapenko	1932	3·5
Magnetron Oscillators		
Breit	1924	60–150
Yagi	1928	15–100
Forro	1929	30–65
Okabe	1929	5–40
Okabe	1930	3–15
Spark Oscillators		
Hertz	1887	50
Righi	1894	2–12
Nichols and Tear	1923	0·18–0·4
Arkadiewa	1924	0·008–0·5

DISCUSSION BEFORE THE INSTITUTION, 30TH JANUARY, 1936

Prof. C. L. Fortescue: The first point in the paper to which I wish to refer is the actual mechanism of the oscillation. The explanation given by the authors is made dependent on the argument that in some circumstances those electrons which succeed in getting across the vacuous space in the shortest time arrive with the lowest velocity. This, however, is probably not the whole explanation, since those electrons which arrive at the higher velocity have acquired their kinetic energy at the expense of the same source, apparently, as that to which some energy will be given in virtue of the low velocity of the electrons which have come across most quickly.

There is another difficulty. The authors in presenting their paper stressed the symmetry of the grid spiral; but, if the oscillation is longitudinal to the spiral of the grid, it would be expected that its initiation would depend on some fortuitous lack of symmetry rather than on exact symmetry.

With regard to Fig. 2, there appears to be as yet no theoretical explanation of why the central part of the characteristic curves should be straight. Do all the tubes which have been used on the transmission described by the authors show as long a straight length as that in Fig. 2?

Passing to Section (3), the interesting point to me is the setting-out of the relative advantages of the array system and the parabolic reflector. Other speakers may have something to say on this subject, and I shall be extremely interested to hear their views.

Turning to the section dealing with reception (page 641), it would be interesting to know how the current at the positive grid of the tube, i.e. the " oscillating electrode," varies at the onset of oscillations, since this change gives some indication of the amplitude of the oscillations which are generated. The effectiveness of the receiver, with its 500-kc quenching system, must depend very largely on this change of current. The authors are almost apologetic for being only barely able to maintain an audible beat note between two micro-ray oscillators. When it is remembered that the beating frequencies are about 2 000 million cycles, and that audibility is in the neighbourhood of 2 000 cycles, and that the degree of constancy is thus 1 in 1 000 000, it will be realized that the authors have no reason to apologize.

Section (5), dealing with propagation, is from the practical point of view the important part of this paper. The authors point out that it is reflection at the surface of the sea to which interference must be attributed. It might be thought that the surface of the sea would generally act more as a dispersive and scattering medium than as a mirror; but at grazing incidence the sea is in fact a mirror, even when rough. This point can be illustrated by using a piece of ground glass as a mirror; it will give a perfectly good image at grazing incidence.

On page 656, reference is made to the use of these very high-frequency currents for medical purposes. In this connection I would suggest that the time is ripe for a close liaison to be established between the Institution and the Medical Research Council. I feel that there are many ways in which our electrical knowledge would be of benefit to the medical profession, and that benefit could be rendered still more pronounced if on our side we knew a little more of the problems with which the medical profession is confronted.

Mr. A. J. Gill: The authors do not give much information as to why they selected the particular type of micro-wave generator which was adopted for their investigation. Was it chosen because it is fairly easily modulated by speech? We in the Post Office have used magnetrons for generating waves of 25 cm wavelength and upwards, but we have not tried to modulate them. I think there is some difficulty in modulating a magnetron by speech. On the other hand, we have found that with a magnetron it is possible to produce more power than with the ordinary type of valve.

With regard to reflector systems, we have applied these 25-cm waves to the ordinary Koomans type of array, and it is very interesting to find that this gives practically the same order of gain on these very short wavelengths as on longer waves. I am not suggesting, however, that the array is better for very short wavelengths; probably the mirror is much more readily constructed, because a certain amount of measurement has to be carried out to get the highest efficiency from any array system, and this would be impossible without measuring equipment—not at present available.

I think the most interesting feature of the paper is the disclosure regarding the fading on the micro-ray circuits. The reasons for the fading, of course, are not very clear. We have the possibility that the beam as a whole is refracted; on the other hand, it may possibly be dispersed. In trying to ascertain whether the beam was twisted, on one occasion the authors rotated the reflector in a horizontal plane and in another case they rotated another reflector in the vertical plane. If the beam had been deflected, it is rather unlikely that it would have been deflected solely in either the horizontal or the vertical plane; it might have been deflected in some other direction, and so these tests are not quite conclusive. If the beam is deflected as a whole, it is rather a disadvantage; because if one had a number of these switches for simultaneous transmission one might get a cross switch between two people who were not intending to talk together. On the other hand, if the beam is dispersed and the drop of 40 db is purely a loss, presumably this loss will be regained to some extent by automatic gain control, provided the power is sufficient at the lower intensity.

It looks as though the cost of the micro-ray system might be a little higher than that of the system we are using, chiefly because of the more expensive structural work required for the towers and large reflectors, as compared with the comparatively cheap type of antenna which one can use with ultra-short waves. On the other hand, the micro-ray system has apparently very much better inherent privacy.

We have been working over a distance of 37 miles, from Scotland to Northern Ireland, using wavelengths of the order of 4 to 6 metres. Six of these radio channels are working in each direction, and they have been in successful operation for over 12 months. Our experi-

ence with regard to fading is similar to that of the authors for these wavelengths; that is to say, for the optical range no fading effect is perceptible. We have also been running a commercial service for the last few months between Shaftesbury (England) and Guernsey (Channel Islands), a non-optical path. We have used very low power, of the order of 5 watts, in the transmitter, but we have been able to carry on a commercial service throughout the summer. In the winter months, however, the service has been unworkable on low powers, a drop of the order of 30 db having been experienced. In the authors' case that is reversed; the micro-ray path is bad in the summer and good in the winter, while the ultra-short-wave non-optical path is good in the summer and bad in the winter. Have any experiments been made to determine the minimum distance over which fading is observed? Also, has any method been devised of measuring micro-ray wavelengths? The paper specifies wavelengths to an order of accuracy of 1 mm, and I should like to know how such measurements were obtained.

On page 656 the authors mention the use of microrays on aircraft and also in therapeutics. The use of ultra-short waves for therapeutic purposes is becoming a very serious nuisance to communication services. There are hundreds of these therapeutic sets being sold at the present time, and they are causing widespread disturbance. This will be felt still more when ultra-short-wave television becomes more general. Anything which can be done, therefore, to suppress interference from these sources at low cost—as, for example, covering the interior of the room in which therapeutic apparatus is installed with a paint of good conductivity—is very important. The authors state that the problem of micro-ray communication with aircraft is no small one, because the majority of external surfaces in aircraft are nowadays either metallic or covered with metallized paint. I should like to ask whether they are sure that the metallized paint used on aircraft forms an effective screen, because all the metallized paints that we have tried are perfectly good insulators! Reflection has been observed from aircraft even on waves of the order of 5 metres, but it has been assumed that this has been due to metallic portions of the fuselage.

Mr. E. S. Byng: During the first tests made from the cliffs of St. Margaret's Bay everyone was impressed with the quality of the speech and the stability of the circuit. At that time we were assured that fading would not occur on these micro-rays, consequently it is rather disappointing to find that this confidence has had to be somewhat modified as a result of subsequent experience. The tests between St. Margaret's Bay and Calais could be made only from time to time, as it would have been rather an expensive matter to have maintained a permanent staff, but the Air Ministry have been very kind in allowing day and night tests to be made frequently on the longer link installed later between Lympne and St. Inglevert, thus enabling the engineers to acquire much information which would otherwise not have been accessible.

To one who is interested in the training of young engineers it would seem that it will be necessary in the future for a radio engineer to have some knowledge of optical science, a field which hitherto has been reserved almost entirely for the physicist. There is much in common between light waves and radio waves. For example, micro-rays can be reflected in just the same way as light waves.

The paper shows how much work has to be done in collecting engineering data before a commercial radio circuit can be established. I can well remember how Mr. Ullrich and other colleagues worked continuously in a little wooden hut at New Southgate before it was possible to arrange for the first trial tests in the one-way demonstration between England and America. Even after this it took years of day and night work in conjunction with the Post Office engineers before sufficient information was collected to demonstrate that two-way commercial radio telephone communication would be possible. Similarly, the micro-ray has been under test for some years and, as Prof. Fortescue remarked, we do not know very much about it even yet.

A few years ago it was the general opinion that wavelengths shorter than about 8 metres were not received at any appreciable distance beyond the horizon and could, therefore, be used to set up a strictly localized service which would be free from interference. We have had to change our ideas in this respect. In an informal discussion opened by Sir Noel Ashbridge about a fortnight ago before the Institution, reference was made to the recent disclosure that some of the television test transmissions made in Berlin were being received in London fairly strongly, as were also the transmissions of the Newark (U.S.A.) police on a wavelength of about 7 or 8 metres. Is there any possibility of using microray and highly directional aerial systems, such as those described by the authors, for point-to-point service without encountering any long-range interference?

We now have information on the characteristics of waves of 16–20 cm and also on the properties of the waves at the other end of the ultra-short-wave section of the radio spectrum. It still remains for someone to investigate waves between, say, 60 cm and 3 metres, thus completing our knowledge of the ultra-short-wave band.

Reference has been made in the discussion to one point which I had in mind, namely the relationship between these ultra-short waves and medical science. The electrical engineer's knowledge of short waves has been of value to the medical profession in dealing with diathermy equipment both for treatment and for surgery, and there is no doubt that further and closer co-operation in this field between engineering and medicine would benefit mankind.

Mr. A. H. Reeves: I should like to touch on two points in this paper; the first is the question of the receiving system and the second that of propagation.

Dealing first with the receiver, it may be of interest to give some information about work done during the last 2 years on an alternative type of receiver to that described in the paper. This receiver, which was tested across the same path as the first experimental circuit described by the authors, was of the triple-detection type, the first intermediate frequency being 10 Mc and the second 500 kc. The overall band width was about 200 kc. The object of trying this receiver was primarily to test out the idea, which is more or less generally

accepted as regards other wavelengths, that a super-heterodyne receiver will give a better signal/noise ratio than one of a super-reaction type—such as the micro-ray receiver with which the superheterodyne was compared. Before a comparative measurement could be made, one or two rather interesting difficulties were encountered. The chief of these was due to instability of the intermediate frequency. An automatic compensating device, similar to that which is now used on some broadcast receivers, was found necessary. This arrangement automatically kept the intermediate frequency within about 5 kc of the correct value; its operation depended on the carrier acting as a pilot channel such that if there were any departure from the correct value a voltage was applied to the plate of the micro-ray beating oscillator tube in such a direction as to compensate for the change, the intermediate frequency thus " locking " itself at the optimum point.

The problem then arose of the correct time-constant to give this automatic tuning device. The first idea tried was to make the time-constant $0 \cdot 1$ millisecond—shorter than the period of the highest audio frequency considered. The advantages of this plan were not only that the random drifts of frequency at either end were compensated, but also that any fluctuations at audio frequency were also smoothed out, the change in intermediate frequency being restored more rapidly than the period of the highest audio-frequency component in the speech. Without such a device serious microphonic noise was sometimes encountered when the wind vibrated the mirror or the tube at either end; with the device in operation this effect was almost entirely eliminated. Another difficulty was that, in spite of the nearly linear curve of modulation with constant frequency, in practice it was found almost impossible to keep this frequency steady during modulation, to the severe limits required here. With this device, however, the difficulty was automatically taken care of, as the frequency-change could be compensated more rapidly than the fluctuations due to speech.

Unfortunately, on the other hand, the system had the disadvantage in practice that spurious oscillations frequently took place at audio frequency. To overcome this an alternative idea was tried—that of using a time-constant long compared with one period of the lowest frequency, i.e. $0 \cdot 1$ sec. This cured the instability trouble; but, of course, the other two advantages (elimination of microphonic noise and compensation of frequency modulation) were lacking. The result was an attempt to use the frequency modulation instead of to avoid it. A modulation peak value of about 2 volts was used on the plate of the micro-ray tube, no audio-frequency voltage being applied to the grid. An amplitude modulation of the order of 1 per cent only was obtained, but also a frequency modulation of about 100 kc—sufficient, when received on the steep portion of the resonance curve of the receiver, to give resulting amplitude modulation, at the receiver output, of about 50 per cent. The latter system, therefore, was found to be the more satisfactory of the two (in spite of the other disadvantages referred to above), because of its freedom from undesired relaxation oscillation; for this reason it was finally chosen for the noise tests.

The resulting comparative measurement showed that the signal/noise ratio of the superheterodyne receiver was between 15 and 20 db better than the maximum observed with the super-reaction apparatus; but additional factors, connected with the ease of unskilled operation, etc., have to be considered before such a receiver is put into commercial service.

I shall now consider very briefly one point in connection with the propagation of 17-cm waves between Dover and Calais, a point which I think is of some interest. The superheterodyne receiver of the second type described above was calibrated as a field-strength measuring set. The calibration was a rather difficult matter, precision being almost impossible, but the final error was believed not to exceed ± 4 db. The field thus measured at St. Margaret's (Dover) from the transmitter at Escalles (Calais) was compared with the calculated value, the effective gains of the antenna-mirror system having been measured, and simple optical propagation being assumed. The maximum field measured was found to be less than the calculated value by about 30 db.

This result is interesting. It seems somewhat unlikely that this minimum loss was due entirely to an out-of-phase reflected wave, produced either locally or from the sea surface, as for a balance of 30 db and greater the limits of phase and amplitude are quite critical. It would not be expected that these close limits could be held; the effect of the tides alone would be more than sufficient to destroy a balance of this order at certain times of the day, if produced by reflection from the sea. It is more probable, in my opinion, that in addition to interference phenomena produced by reflected rays (almost undoubtedly present) there exists at these frequencies some source of attenuation on the optical path; an attenuation which, in the case mentioned here, attains the comparatively high value of about 30 db.

Mr. E. C. S. Megaw: Many of us who have been interested in the production of extremely short waves will have been surprised to find how narrow is the range of the frequency spectrum in which fading due either to ionospheric effects or to atmospheric effects is completely absent. One had long imagined that, for short-range circuits, micro-rays would provide complete relief from many of the troubles to which we are accustomed on longer wavelengths; that this is not quite the case with regard to fading is evident from the results given in the paper.

Dealing with the question of propagation, and the related question of reflector systems, it would appear, from the results, that the reflector gain used in the authors' circuits is in the neighbourhood of the economic limit. Indeed, in certain circumstances of propagation that limit may even have been exceeded, and one is encouraged to consider what would be the economic aspect of an increase in power and a decrease in reflector size. For instance, it is possible at the present time to consider an increase in power of the order of 10 times compared with the power used on this circuit, and that would enable the reflector diameter to be reduced to about one-third for the same signal/noise ratio. A smaller reflector would no doubt make the problem of mast design easier, and enable higher masts to be built

for a given cost. Do the authors consider that higher masts are likely to improve the circuit?

With regard to the question of the best way of generating such frequencies as those associated with microrays, I do not think anyone is in a position to give a definite answer to that question as yet. From the point of view of power and efficiency only, there is something to be said for the tentative view which I put forward* some years ago, namely, that the type of oscillator in which a magnetic field co-operates in producing these " transit time " oscillations has definite advantages; but, as Mr. Gill has also indicated, there are other troubles. Modulation is perhaps, with conventional methods, more difficult.

It will, I think, help to clarify our ideas if I give some particulars of a magnetron valve comparable in size and power dissipation with the authors' micro-ray tube. The magnetron valve to which I refer is capable of working at a similar wavelength of 25 cm, and also over a wide wavelength range extending from 22 cm to perhaps 35 cm. At 25 cm its output and efficiency are in the neighbourhood of 4 times those of the valve described in the paper. The most interesting difference from a practical point of view is that such a valve requires a high anode voltage and a low current, as distinct from the micro-ray tube, which needs a rather low voltage and a rather high current. From the point of view of initial cost the former is at a disadvantage, because a high voltage costs more to provide; from the point of view of valve life, however, it is at an advantage, because a filament of given size will last longer if the required emission is smaller. How far those factors balance one another economically, or which is the more valuable, I leave to those who are more concerned with operating conditions to decide.

The difficulty and expense of producing the magnetic field which is required by the magnetron have perhaps been exaggerated. With a typical electromagnet, weighing about 15 lb. complete with valve mounting, the power required is about 5 watts, i.e. perhaps 3 times the output power, but in absolute terms this is a negligible amount of power for any communication system. Alternatively, permanent magnets made of the magnet steels which have recently become available offer a simple and in many ways very satisfactory solution of this problem. Their power consumption is zero, and, what is much more important, the problem of frequency stability is considerably simplified. A permanent magnet can easily be made to produce a very constant field. That field can be adjusted by simple devices throughout a range which will provide tuning over, say, 1 octave of frequency. The point about the frequency stability is really this. In the magnetron used to produce microrays the frequency is primarily controlled by the magnetic field. The changes produced by variations in anode voltage and anode current are appreciable, but in the nature of second-order effects. In the case of the triode, the grid voltage is the primary controlling factor, so that if the magnetic field is constant it is obvious that the problem is greatly simplified.

There is one last point to which I should like to refer. In all valves, of at any rate the well-known types, which

* *Journal I.E.E.*, 1933, vol. 72, p. 313.

can be used for such wavelengths as those employed in micro-ray work, it is an essential condition that the filament must be worked at such a temperature that the anode current is decided by that temperature;* in other words, very small changes of filament voltage produce relatively enormous changes in the emission and so in the frequency and amplitude of the signals. That problem is aggravated by the fact that bright-emitter filaments are essential, and their resistance changes during their life. We must therefore compensate not only for mains variation but also for internal variations in the filament. In an attempt to get over this difficulty an automatic compensation circuit has been developed by one of my colleagues and myself which offers the hope that such circuits may eventually be able to operate without continuous attention for periods of at least some hundreds of hours.

Mr. W. T. Gibson: The development of the micro-ray tube has been a very interesting study. A very large number of tubes have been made up, primarily to cover the wavelength range from about 9 cm to about 30 cm. In that range, tubes can be made for any required wavelength, but it is necessary to construct the tube for the wavelength required. With any given tube there is an optimum wavelength at which the greatest power is given, but that tube can be used over a range of roughly 6 per cent on either side of the optimum. The valves used in the cross-Channel links are identical for the transmitter and the receiver, except that in the transmitter valves the diameter of the anode is rather greater.

In the early days of the construction of these tubes, there was very considerable difficulty in maintaining the elements in the positions required. For example, the grid always tended to sag, and it became evident at a very early stage that the lack of concentricity of the elements was reducing the output of the tube. As a result, a very great effort was made to improve its geometrical design, and the first step taken was to pump the tubes with the axis of the grid vertical, so that any sagging which took place resulted in a variation of the pitch of the grid along its length, without any change in the concentricity. At one time it appeared that this variation of pitch along the length of the grid might possibly be giving an improvement in the operation of the tube, but further study showed clearly that this was not the case; and, when it became possible to make a tube in which the pitch of the grid was absolutely constant along its length and the elements very exactly centred, it became quite clear that that was the optimum condition, and that the variation of pitch along the grid was not necessary and, in fact, was detrimental.

The manufacture of these tubes is rather a difficult matter, in view of this very strict geometrical requirement, and it has been necessary to give very careful heat treatment, particularly to the grid, in order to ensure that it will maintain the required position. This heat treatment must be of such a nature that it leaves the surface of the grid in a highly polished condition. The use of wire for the grid which has a roughened surface decreases the output of the tube, possibly

* For an exception see B. J. THOMPSON and P. D. ZOTTU: *Proceedings of the Institute of Radio Engineers*, 1934, vol. 22, p. 1374. The efficiency of their value appears, however, to be very low.

owing to an effective increase of the high-frequency resistance.

As the authors mention, in the early experiments the tube was mounted in the reflector, whereas in the later ones the tube was mounted behind the reflector and fed through a transmission line. This point has a slight bearing on the design of the tube, in that if the tube is placed inside the parabola the radiation passes through the tube, and it has been found that the use of a " getter " seriously interferes with the radiation pattern of the waves leaving the reflector. When the tube is mounted behind the reflector, the use of a getter is attended with no serious consequences.

It is essential that the vacuum in these tubes should be extremely high. Both ends of the grid are, fortunately, brought through the glass envelope, and advantage of this has been taken to provide for the pumping of the tube. The degassing is done by passing current through the grid, and thus it is possible to get the whole of the grid heated to a much more uniform high temperature than is ever possible by electron bombardment. It is only by very great care being expended on all these details that a sufficiently high vacuum can be obtained. If the vacuum is not extremely high there is a loss of output of the tube, and instability; often the tube will oscillate on a spurious frequency, frequently about half of the required value.

The commercial testing of the tube is rather interesting. The tube is mounted in a small transmitter, and feeds a dipole through an impedance-matching transformer and transmission line, and a few feet away is a receiver consisting of another dipole connected to a transmission line and transformer which feeds a thermocouple. The characteristic curves are plotted for, and supplied with, each tube. The information they give enables the tube to be put into service immediately under the best operating conditions.

In the testing of the tube in the factory, one difficulty is the formation of stationary-wave patterns round the apparatus, which force the operator to remain in a stationary position while the measurements are being taken. Any appreciable motion of his body will affect the pattern and alter the readings.

It is very necessary that the terminals of the grid should be exactly spaced, as they feed directly into a rigid transmission line. This has been a serious difficulty, as it has meant carrying out the glass-working to an extremely high degree of precision. In fact, with the very rigid transmission line at present used, it is necessary to introduce a slight flexibility in the grid leads external to the tube.

I should like to ask the authors a question in connection with the interference which has been shown to exist between a reflected wave and a direct wave on the cross-Channel links. Interference of this sort leads one to expect a minimum with a particular water height, and therefore this minimum should occur at a certain stage of the tide. As the height of the tide varies from day to day, the time at which the minimum appears should vary. One would imagine that at the period of the neap tides the minimum might occur closely in time on either side of high tide. If that were the case, one would expect the minimum to occur much earlier and much later on either side of high tide in the case of the spring tides. I should like to know whether there is any evidence of such an effect.

Mr. R. A. Watson Watt: The commercial future of micro-ray communication seems to me to depend so greatly on problems of frequency stability, and on the magnitude of the fading problems that have been outlined, that I should like to ask whether there will be available at an early date a considered statement of the attainable frequency stability of an ordinary " massproduced " system for micro-ray communication. The cynic may say that a single circuit of this character is a " stunt "; he would be bound to admit that a hundred circuits of this character are a service. The demand for increasing numbers of communication channels which may be worked continuously and independently is such that we are being driven towards the very-high-frequency end of the radio spectrum, but as we approach that end I imagine that the problems of frequency stability increase at a very alarming rate. Do the authors feel that there is a possibility that 12, 20, or 100 frequency channels might be operated systematically, without serious mutual interference, in one area and over such distances as the cross-Channel service? One would also like to know whether the fading phenomena discussed in the paper are such as to render the circuits uncommercial for any high proportion of the day, on the average of a period of a week or so at a time.

The radio physicist would no doubt welcome a consistent series of observations of the same character as the authors have given us, but with still closer study of the meteorological conditions with which these fading phenomena are associated. The verbal summary which the authors have given is extremely puzzling to the meteorologist. On the general theory of fading which they favour, the lack of correlation between signal strength and atmospheric pressure is surprising, because one would necessarily expect that the mean height of the barometer would, at least indirectly, determine air turbulence, which in turn would modify the propagation phenomena.

Mr. J. F. Shipley: I agree with Mr. Watson Watt's view that the meteorological conditions that the authors have mentioned are very puzzling. For instance, they say that the propagation of these micro-rays is independent of the potential gradient in the atmosphere, and yet that it varies directly a fog appears, for fading occurs during fog. It is well known that the potential gradient is much greater during times of fog than normally, and therefore I cannot understand why fog conditions should cause fading of the micro-rays. It is also stated in the paper that their propagation does not seem to be affected by rain, hail, and thundery weather. Possibly this is because such effects are very local, whereas micro-ray propagation is dependent upon general atmospheric and optical conditions in which refraction in the atmosphere probably plays a great part.

As to the commercial side, only last week I was asked by a client whether I could introduce to him a new method of communication which would enable him to telephone orders and instructions over short distances, up to 50 miles. The authors perhaps do not realize

what a great field awaits them in foreign countries among mining concerns situated in places where there is little possibility of communication and where, say, a distance of 5 miles may mean a journey of as many days. Such situations are mostly associated with the meteorological conditions they describe as difficult.

Mr. W. E. Benham: In addition to the micro-ray tube and the magnetron methods there is a third method which uses a negative-grid tube specially designed for low transit-time losses. The efficiency of oscillation obtained by C. E. Fay and A. L. Samuel,[*] using negative-grid triodes, appears to be higher than the micro-ray efficiency, and the method is possibly capable of development.

(*Communicated*) Prof. Fortescue has called attention to our imperfect understanding of what really happens in

displacement and therefore no negative leakance, if $\partial i/\partial x$ is taken as zero, we cannot neglect mutual repulsions of electrons in our explanations; in other words, we may say that mutual repulsions are a necessary condition for negative leakance.

It may be noticed that the mutual attractions between the electrons and the electrode charges they induce can in the last analysis be ascribed to mutual repulsions; since the positive charges in the metal are relatively immobile, a positive charge at the surface is brought about by the repulsion of free electrons further into the metal. The positive charges will exert restoring forces on the displaced electrons, a fact which requires further consideration. Now, since $\partial i/\partial x = - \partial \rho/\partial t = |= 0$, we cannot neglect the displacement current corresponding to charges induced by the electrons on the electrodes; in other words,
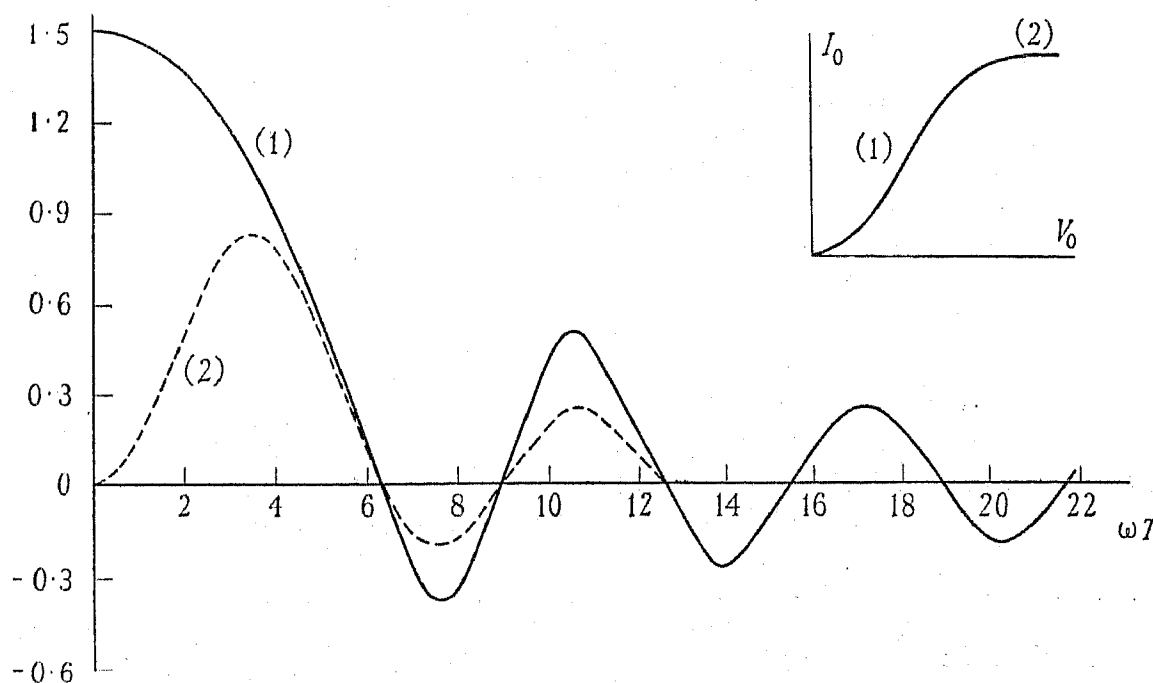
Fig. A

To obtain diode conductance, multiply ordinates by I_0/V_0. To convert to leakance (in application to micro-ray work) multiply also by l^{-1}, where l = length of grid wire.
Example. $I_0 = 70$ mA, $V_0 = 360$ volts, $l = 19$ cm; reading from dotted curve, maximum negative leakance is $0 \cdot 2 \times \frac{70}{360} \times \frac{1}{19}$ = 0·002 mA volt⁻¹ cm⁻¹, occurring at $\omega T = 7 \cdot 6$.
In view of grid "transparency" the principal negative-conductance region is misplaced slightly towards the right of the diagram.

vacuum tubes at very high frequencies. The authors cite as the cause of the negative leakance the mutual attractions and repulsions between the oscillating electrode charge and the electrons inside the tube. In order to check this statement, we may try the effect of neglecting that part of the displacement current corresponding to charges induced by the electrons (the inter-electrode displacement current having in any case no contribution to make to the leakance). We then find that the external-circuit current is equal to the electron convection current, and that the latter would have a constant value across the inter-electrode space; in other words, we find $\partial i/\partial x = 0$. But, by the familiar relation $\partial i/\partial x = - \partial \rho/\partial t$, this would entail $\rho = 0$, except at zero frequency. Now ρ corresponds to the electron density in the space, and, while ρ may be small in the case of voltage saturation, $\partial \rho/\partial t$ is far from being small owing to the high frequency. Since theory gives no phase

we cannot neglect the mutual repulsions between the free electrons in the inter-electrode space and the free electrons in the metal of the electrodes. It has already been indicated, however, that mutual repulsions of the free electrons in the inter-electrode space cannot be neglected. Hence we can conclude that mutual repulsions between all the free electrons concerned, whether in the inter-electrode space or in the metal, constitute a necessary condition for negative-leakance effects. Another necessary condition is that the product ωT shall have certain values, where T is the transit time and $\omega = 2\pi \times$ frequency. At low values of ωT the leakance (except in certain cases, such as the negative-grid plane saturated triode)[*] is always positive, but over certain ranges of ωT the leakance works out negative. The necessary and sufficient condition for negative leakance thus at first sight appears to involve both mutual repulsions and transit time. Since, however, $T = f(V, x)$, and $\rho = \phi(V, x)$, transit time may be ex-

* *Proceedings of the Institute of Radio Engineers*, 1935, vol. 23, p. 199. See also B. J. Thompson and G. M. Rose: *ibid.*, 1933, vol. 21, p. 1707.

* C. J. Bakker and G. de Vries: *Physica*, 1935, vol. 11, p. 683.

pressed in terms of ρ, and we may therefore say that mutual repulsions bring it about that at some frequency there will be a negative leakance. Conversely, ρ may be expressed in terms of T, so that with equal veracity we may say that the finite transit time brings it about that at some frequency a negative leakance will arise.

An exception should here be mentioned. It appears that a space-charge-limited cylindrical diode with small filament may never show negative leakance. Thus those electrons which are collected by the micro-ray grid in the direction filament-to-grid contribute positive leakance if the grid potential is insufficiently high. This result explains the importance of working in the emission-limited condition. It may, however, be proved, assuming the grid-plate space to be planar, that space-charge limitation *here* would be advantageous; for given geometrical conditions, therefore, we have two opposing tendencies, accounting in part for the low efficiency.

Fig. A illustrates how negative leakance may be obtained owing to electrons collected by the grid in the direction plate-to-grid, assuming the plate-grid space to be planar. It will be seen that the negative leakance obtainable is greater in the space-charge-limited region in a ratio exceeding $1\cdot8:1$. Fig. A provides an explanation which does not depend on the third electrode; grid transparency and multiple transits may be taken into account to a reasonable degree of accuracy.*

Mr. H. Archer Thomson: I should like to know what is the order of the frequency-spread with maximum modulation, firstly with combined anode and grid modulation, and secondly with grid modulation only. Also, what is the long-period stability of the circuit described in the paper, and how often has it to be readjusted?

Dealing with the question of modulation, in the case of the magnetron, with 50 per cent linear amplitude modulation the frequency-spread is of the order of $0\cdot5$ per cent without any compensation. It is possible that this figure is capable of a great deal of improvement. Experience shows that the " acorn " valve does not give very good results as a receiver on a wavelength of 25 cm, whereas the magnetron does.

Mr. W. J. Brown: The authors are very modest in the list of applications which they claim for micro-waves. I should like to ask in particular whether they have considered extending the beacon application, which they mention, to the whole question of fog protection at sea. Provided it was possible to install a micro-wave or even an ultra-short wave transmitter and receiver on all ships at sea, during times of fog the transmitters could be operated continuously and radiate a warning which would be picked up only by other ships within the danger area. Such an arrangement could not be used with long waves, because of the jamming which would occur between ships quite a long way apart.

I should also like to ask the authors whether in the development of the tubes for generating these micro-waves they have experienced any difficulties due to dielectric losses in the seals. Some years ago, when developing tubes for rather longer wavelengths, of the

order of 200 cm, I found that it was very desirable to insulate or support the electrodes of these tubes at nodal points on the circuit in order to eliminate seal losses.

Mr. O. S. Puckle (*communicated*): It would be interesting to know whether the authors have used push-pull transmitting systems, or whether attempts have been made to use two or more transmitters in parallel in order to increase the power output. It is, of course, appreciated that the system used by the authors has not so much to gain by the use of push-pull as has that developed in Italy under the direction of the Marchese Marconi.

I was engaged for some months in England and later in Italy under the Marchese Marconi on work similar to that described by the authors, and during this period discovered that a great increase in output power could be obtained by the use of Lecher-wire transformers in the anode, grid, and filament circuits. It is therefore surprising to note that the authors have found such precautions unnecessary, and it would be of interest to know whether the device has been tried. It would appear that, far from being of a high impedance at the ultra-short wavelength in use, the filament leads used by the authors would act as a line of infinite length, in which case the impedance would be of the order of 100 ohms. Needless to say, the losses in this case would be of some importance and a very definite improvement should be obtained by the adoption of Lecher-wire transformers.

The authors' choice of a mirror as compared with Mathieu's fish-bone type of reflector is of great interest. The fundamental advantage of a mirror would appear to be its ability to radiate a circularly-polarized wave, but this property cannot, in general, be made use of unless the aerial forms a point source, which it does not. The mirror also possesses the property of aperiodic action, so that its operation is not dependent upon the angle between the aerial and a given aperture-diameter line. For this reason it is possible to make tests with either vertically or horizontally polarized waves without rotating the mirror, as is necessary with the fish-bone type of reflector. On the other hand, the effect of the wind on the mirror must be of some importance. The fish-bone type has the advantage that where a transmitter is already in existence and it is desired to increase the power, another transmitter may be set alongside the first at the appropriate distance and the two circuits may be coupled together by means of the filament-circuit Lecher-wire transformers so that they operate in phase. It is not easy to see how this could be done with the mirror form of reflector.

Since it is easy to test different angles of polarization with the mirror reflector, it would be of interest to know whether vertically-polarized signals were always received at their greatest strength when the receiving dipole was also vertical, or whether rotation of the plane of polarization was ever observed. I am of the opinion that horizontal polarization of the transmitted wave gives a slightly higher signal strength at the receiver than does vertical polarization at these high frequencies, unless the dipoles are many wavelengths above the ground, and that it also provides a higher

* See H. ALFVÉN: "Inaugural Dissertation to the University of Upsala," 1934; also W. E. BENHAM: *Wireless Engineer*, 1935, vol. 12, p. 3.

signal/noise ratio; the authors' opinion on these points would be welcome.

The results obtained by raising the transmitter without a reflector do not agree with those obtained in Italy or in Japan. This effect is almost certainly due to the fact that the latter results were obtained at distances which were necessarily a smaller number of wavelengths from the ground. Had it been convenient in Italy to place the aerial as many wavelengths from the ground as the authors were able to do, it is practically certain that agreement with their results would have been reached.

Rumbling noises, similar to those obtained by the authors, were heard in Sestri Levante during the month of October, 1931, on one or two occasions during the last half-hour before sundown. On the occasions referred to the whole of the sky in the neighbourhood of the sun was illumined with a constantly-changing colour of light varying from a deep purple to a brilliant green, and for the whole of this period a rumbling noise of more or less constant frequency and amplitude was heard. It should, however, be noted that the authors' opinion that the effect is due to the state of the tide was not applicable to the case referred to above, as the Mediterranean is a tideless sea.

Another interesting phenonemon was the reception of the Genoa broadcasting station on a receiver tuned to approximately 70 cm on board the " Elettra " in Genoa harbour. Some of the preliminary work was carried out at Croydon aerodrome, and it is of interest to note that no disturbance was ever obtained from aeroplane engines.

The Clavier circuit is extremely interesting, and a full description of the reason why it gives a better signal/noise ratio and of the connection between " Clavier frequency " and signal/noise gain would be appreciated.

Messrs. W. L. McPherson and **E. H. Ullrich** (*in reply*): Prof. Fortescue remarks that both the energy-giving and the energy-absorbing electrons have obtained their energy from the same source. It is more easily seen from the mathematics than described in words why a credit balance exists in favour of oscillation. The deciding factor is the shorter transit time taken by the oscillation-sustaining electrons.

Symmetry of the grid spiral is a matter of great importance, as is emphasized by Mr. Gibson. The initiation of oscillations may be due to some irregularity of filament emission, but is independent of grid symmetry. It is usually accompanied by a change in grid current of 1 to 2 mA, i.e. about $1\frac{1}{2}$ to 3 per cent.

Fig. 2 was not specially picked to illustrate the linearity of the characteristic curves. It was chosen at random, and in fact very many better examples could have been selected, although perhaps the degree of linearity in the figure has been slightly exaggerated by the limitations of drafting.

Mr. Gill is correct in assuming that the particular generator circuit used was chosen on account of its adaptability to amplitude modulation. It is agreed that considerably larger power can be obtained from valves of the magnetron type, but so far amplitude modulation of magnetrons has not been very practicable.

With regard to the tests as to twisting of the beam,

it must be pointed out that tests by rotation of the reflectors about either a vertical or a horizontal axis were made not once but repeatedly, and might reasonably be expected to show up the appropriate component of any deflection of the beam. The negative character of the results of these tests seems fairly conclusive evidence that deflection of the beam is rare. In any case the connection of a subscriber to an unwanted correspondent owing to the switching to which Mr. Gill refers would only be dangerous if the adjacent micro-ray links operated on the same wavelength.

No experiments have been made to determine the minimum distance over which fading is observed.

In connection with the value of metallized paint in forming a reflecting surface, a coating of such paint consists in effect of a series of metallic scales overlapping but insulated by a thin film of dielectric. This may be a perfectly good insulator at low frequencies, but at very high frequencies the capacitance reactances become so extremely small that the sheet of paint is much more in the nature of a poor conductor than a good insulator.

The wavelengths have been measured by the displacement of a bridge along a transmission line and may give an absolute error of 2 to 3 per cent. It is, however, possible to measure relative wavelengths to 1 or 2 parts in 1 000.

Mr. Byng inquires as to the possible use of micro-rays for providing localized point-to-point services without long-range interference. So far as our present knowledge goes, the likelihood of long-range interference seems remote, a factor to which weight must certainly be given in considering the provision of short-distance point-to-point schemes.

Apart from his interesting description of his super-heterodyne experiments, Mr. Reeves brings out the very important point that he calculates a loss somewhere in the transmitting medium of the order of 30 db, assuming simple optical propagation. It is agreed that there does exist a considerable unexplained attenuation, which cannot well be attributed to interference of the type discussed in the paper. If we accept the figure of 30 db over a distance of 36 km as due to absorption, i.e. 0·83 db per km, we should expect for the 56 km on the Lympne–St. Inglevert link an absorption loss of 47 db, to which must be added approximately 5 db due to propagation, assumed optical. An attenuation of this order is not, however, encountered. This suggests that the unexplained loss is a terminal loss which may be due to interference arising from local diffraction at the cliff edges near the transmitter and receiver, such diffraction being very nearly constant, as it would not be affected by tide level or by normal changes in the refractive properties of the atmosphere. Apart from local diffraction, some of the loss mentioned by Mr. Reeves may have arisen from the elliptical polarization used during his experiments (see page 642). We should not like to reject altogether the possibility of absorption, however, since it has been shown by Prof. N. H. Williams[*] that 1·5-cm waves are strongly absorbed by ammonia gas.

Mr. Megaw asks whether higher masts are likely to improve the circuit. This is rather a problematical

[*] *Proceedings of the Institute of Radio Engineers,* 1934, vol. 22, p. 815.

question. On the assumption of optical visibility between the stations and a single point of reflection, analysis shows that there is a series of optimum station heights for any particular wavelength and distance. High masts, however, have the advantage of reducing the magnitude of local diffraction effects.

An increase of 10 times in the output power would make possible a reduction of the diameter of the mirror to one-third at one end of the link only; or, alternatively, a reduction of about 40 per cent at each end. We think, however, that though a tenfold increase in power may be possible, the sizes of the mirrors should not be reduced. The return will then be a reduction in the lost traffic hours.

In his survey of the development of micro-ray tube manufacturing technique, Mr. Gibson refers to the difficulty during testing which arises from the formation of stationary-wave patterns around the apparatus. It is interesting to note that this same difficulty was experienced by Hertz and by Sir Oliver Lodge in the course of their early work on micro-ray measurements.

As regards interference due to reflection from the sea surface, the correlation of a minimum signal with a particular water height is difficult, as the effect tends to be obscured by the variability of curvature of the ray paths involved. Nevertheless, from our study of the signal-strength curves, we feel that such an effect is present.

Mr. Watson Watt apparently has in mind the question as to how closely it would be possible to space micro-ray communication circuits if they were installed in large numbers. We must frankly confess that we are not in a position to answer this question; at the present time we should feel obliged to apply a liberal safety factor and ask for a spacing of 3 parts in 1 000. Although we should hesitate to take the responsibility for recommending, in the present state of the art, the installation of 100 micro-ray channels in one area, there is no reason to say that such a communication system is not possible.

As Mr. Gill points out, most of the fading variation can be corrected by automatic gain control. The signal/noise ratio, however, in the fading troughs is not sufficiently good to maintain a commercial telephone service. Figures for the Lympne–St. Inglevert circuit are not available, but on the St. Margaret's–Escalles link a telephone service can be maintained throughout the winter, and for about 80 per cent of the time during the summer months. These figures can be considerably improved by the simultaneous use of two wavelengths in each direction, the circuit being then commercial for 95 per cent of the time. This does not necessitate doubling the whole equipment, as it is possible to radiate two wavelengths from one aerial system, provided that the polarizations are at right angles.

Mr. Shipley mentions that the potential gradient is much greater during times of fog than normally. It is pointed out in the paper that fog conditions, once they are stable, do not cause fading; it is only during the changing of conditions, i.e. during the settling of a bank of fog, that fading is liable to take place. Mr. Shipley also mentions that the effects of rain, hail, and thunder, are very local. While it is impossible to be sure that the same conditions prevailed over the entire

length of path, it has been definitely established that the propagation is not affected by rain, hail, or thundery weather at both ends of the link and forming part of the general weather conditions over a wide area.

Mr. Benham points out quite rightly that any complete theory of micro-ray generation must take account, not only of the attractions and repulsions between the electrode and space charges, but also of the mutual repulsions between the free electrons themselves, since the former are in the last analysis to be ascribed to the latter. It must, however, be possible to explain the mechanism of oscillation qualitatively without reference to mutual repulsions between free electrons, seeing that as the oscillating electrode potential is made increasingly high the relative importance of the mutual repulsions becomes increasingly less. This justifies A. G. Clavier's simplification, which gains in ease of practical application what it lacks in theoretical completeness.

With regard to Mr. Thomson's questions, the long-period stability of the circuit is primarily a matter of the operating voltages. Provided that these are held at the correct values no other readjustment is normally required. The adjustments found good at the beginning of the day hold good for at least the next 12 hours. There is, of course, a gradual change in the operating conditions arising from the changes in filament diameter with ageing, but these do not in general make themselves felt until the tube is approaching the end of its life.

The frequency-spread with maximum modulation on both grid and plate depends upon the accuracy of the compensation. With modulation on the grid only, there is a variation between 10 and 20 megacycles, i.e. of the order of 1 per cent.

Mr. Brown raises the question of the use of micro-ray beams for fog protection at sea. This has, of course, been considered, but we have had no opportunity of studying the practical problems which arise. The main obstacle to the introduction of such a system is the lack of experience of wireless operators with equipment of this kind.

No special difficulties with dielectric losses in the seals of the tubes have been encountered, but it must be remembered that the power generated at 18 cm is very small, and a relatively high percentage loss might easily occur and yet not be observed. It has been found advisable in the tubular transmission lines to place the insulators at nodal points.

With reference to Mr. Puckle's observations, two tubes have been operated in push-pull fashion and found to give approximately double the output. The circuit was then, however, rather too delicate in adjustment to make the system really commercial.

The transmitting circuit used is quite different from that employed in the Italian experiments, its special features being that the filament is at earth potential and that the filament leads do not carry high-frequency currents. There is therefore no improvement when the filaments are fed through Lecher-wire transformers.

Mirror reflectors, of course, can be mounted side by side and energized in phase by connecting the aerials, through tubular transmission lines of suitable lengths, to a common generator.

Under normal receiving conditions, vertically-polarized

signals are always best received when the receiving dipole is vertical. No rotation of the plane of polarization has been observed. On these wavelengths there does not seem to be any appreciable difference in signal strength with horizontal or with vertical polarization. As mentioned in the paper, the Lympe–St. Inglevert circuit operates with " go " and " return " channels polarized horizontally and vertically respectively, but no difference in efficiency has been found between the two. For some time both circuits were operated with vertical polarization without any noticeable gain or loss as compared with the regular practice.

The note on rumbling noises observed in Sestri Levante is very interesting, but no immediate explanation can be offered. The peculiar coloration of the sky suggests, however, that the phenomenon was certainly connected somehow with the refractive conditions of the atmosphere. Tidal effect would not, of course, be involved in this case, as it would show up only in slow-period fading.

Reception of the Genoa broadcasting station on a receiver tuned to 70 cm suggests that the receiver was operating primarily as a detector and had small selectivity properties at micro-ray frequencies. We have observed very similar phenomena at Lympne using a receiver operated in accordance with adjustment 1 of Table 1, in which the detecting action predominates.

It is expected that an article dealing with the receiver shown in Fig. 15 will be published by A. G. Clavier in the near future.

DISCUSSION ON

"EQUIPMENT AND PERFORMANCE OF STEEL-TANK RECTIFIER TRACTION SUBSTATIONS OPERATING ON THE UNDERGROUND RAILWAYS OF THE LONDON PASSENGER TRANSPORT BOARD "*

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT LIVERPOOL, 20TH JANUARY, 1936

Prof. F. J. Teago: We, in Liverpool, are particularly interested in the subject matter of the paper, because for the past 4 years we have had a lecture course dealing with the design and construction of mercury arcs. I think that the author has every reason to be enthusiastic over such arcs, because the more one knows them the more one likes them. We have had a lot of experience here with demountable mercury seals and find that they are not satisfactory because mercury does not wet steel surfaces; if one dismantles a mercury seal once or twice, one finds that the surfaces have become oiled and that the seal fails to function. It must be remembered that the vacuum in the mercury-arc container is extremely high and that it is difficult to keep a mercury seal tight for long. The author mentions that the usual rate of leakage over the mercury seals is about $\frac{1}{2}$ micron per hour. I much prefer the vitreous enamel seal, which is a perfectly sound engineering job and cannot go wrong. I regard the McLeod gauge as quite unsuitable for permanent operation. The Pirani gauge, however, although not a primary system—it has to be calibrated against a McLeod gauge—is very robust and, if calibrated at two or three points, will give reliable readings at very much lower pressures than the McLeod gauge will. The author mentions that he has been using groups of three separate transformers for feeding the arcs and that next time he is going to fit the usual 3-phase core type. This is a very sound move, because if one attempts to load a system between the neutral point and one line, as is done in the case of the mercury arc, only a small load can be carried if the supply is obtained from a bank of three single-phase transformers.

Mr. F. E. Spencer: Some time ago I had the opportunity of visiting one or two of the Northern Extension substations, and I was very much impressed by the performance of the plant. I thought it very remarkable indeed, on going into the building in absolute darkness and switching on the light, to find plant of 4 500-kW capacity working entirely unattended; it seemed a very great tribute to the reliability of modern electrical plant in general. I was rather struck, too, by the large size of the substations and the amount of space occupied. We all know how very expensive land is anywhere in London, not only in the city but also well out in the suburbs, and it seemed to me that the capital cost of the substations must be considerable. The layout struck me as being excellent throughout.

I am rather surprised to find that the use of three single-phase air-cooled transformers has been preferred to that of 3-phase transformers. I note, however, that the latter are to be installed in future, and I should like to know whether these are to be air- or oil-cooled.

I gather from the author's verbal remarks that the future policy of the L.P.T.B. will probably favour rectifiers rather than rotary convertors. Although the proportion is only 10 per cent of rectifiers to 90 per cent of rotary plant, with 37 units and a capacity of 58 000 kW the Board must have sufficient plant installed to enable them to form quite a sound opinion as to the relative merits of the two sets of plant. My own view is that the rectifiers always have the advantage.

I understand that no corrosion of the rectifier tanks has occurred at the Hendon substation, where tap water is used for cooling purposes. The author did not mention the nature of the water, but I am under the impression that London water generally is fairly hard, and that there would be no trouble due to moorland water such as we have in this district.

Mr. R. Varley: How do the maintenance costs of mercury-arc rectifiers compare with those of rotary convertors? Rectifiers require numerous pumps and auxiliary equipment, which it seems to me must be subject to a fair amount of wear and tear.

I should also like to ask how the cables are secured on the vertical runs at Leicester Square substation.

Mr. H. Rissik: The paper constitutes a very striking indication of the fact that the modern mercury-arc rectifier is the coming type of converting plant for traction work in this country. Further, I do not think it is too much to say that it is the coming type of converting plant in every case where one wants to get direct current from alternating current, and get it as cheaply as possible, not only as regards running and maintenance costs but also as regards capital costs of buildings and foundations.

I am very much struck by the general similarity in layout between some of the London Underground stations and the rectifier stations put down in Berlin some years ago. One particular point which the author brings out is the fact that one can put rectifiers upstairs, an important advantage where sites are valuable. Thus it is quite possible to build rectifier substations vertically instead of horizontally; but in the case of the Berlin substations this policy has been pushed to an extreme. As far as I know, the substations which the

author describes are the first of that standardized type to be adopted for traction work in this country.

I should like to refer to the effect of the rectifier on the a.c. supply. The predominating effect is distortion, which is most noticeable where the ratio of the rectifier-plant capacity to the installed kVA of generating plant is fairly high. If one takes, for example, a manufacturer's test-bed where the supply is commensurable in output to that of the rectifier to be tested, one gets effects which give totally different operating characteristics from those which one would expect from a purely design point of view. In the case of the Underground system, I gather that in spite of the high ratio of rectifier kW to generator kVA, the distortion of the voltage wave produced by the rectifiers is not as noticeable as that which one may get from other causes. I do not consider that the distortion would be reduced by a change in primary connection. Actually if one analyses the current wave of a 6-phase rectifier, taking first the input current with a delta-connected primary and then the input current with a star-connected primary, one gets totally different wave-forms but exactly the same percentage of harmonics in the two cases. In the one case, however, the harmonics are in anti-phase with those in the other case. I think that in the system which the author has described this feature has been made use of, although perhaps not consciously; because it so happens that the primaries are delta-connected on the one extension and star-connected on the other. Therefore one gets an improvement in the wave-form due to the fact that the several harmonics, being in anti-phase in the two cases, cancel one another out, even although the extensions of the system are so far apart. This is a point which is sometimes taken care of consciously. I know of cases on the Continent where this feature has been made use of, two rectifiers of the same size being run in parallel with one another in the same station.

I am very often asked " Can you improve the power factor of a rectifier by any means?" The power factor given as a rule for a 6-phase rectifier is 0·93, and theory indicates that one cannot get a higher figure than 0·96. There are two factors which tend to pull down the power factor, namely the harmonics and the reactive kVA taken by the transformer. The reactive kVA can be reduced to zero by including static condensers. There is no known means of eliminating the harmonics, apart from introducing some type of rotating machine and adjusting the various harmonics generated so that they are out of phase with those produced by the rectifier. I believe a machine of this type has been tried out in Scotland in connection with the grid, but I do not know whether success has been achieved.

The straightforward rectifier is sound and simple, and has been developed to a pitch where it compares more than favourably with any other type of converting plant. When we come to some of the newer and more revolutionary of its applications, however, such as the static frequency-changer, all kinds of commutation troubles arise. The rectifier is a commutating device, and, whilst natural commutation is simple and reliable, forced commutation is not always so stable under all possible conditions of operation. In some of these later applications the commutation is forced by a process called grid control. This aspect of the rectifier is really the most interesting of all. It is as yet in its infancy, especially where inversion is concerned, but a great number of practical applications have so far appeared.

I should like to mention two of these; firstly, the use of two rectifiers connected back to back on the d.c. side so as to form a static Ward–Leonard set. This application has been successfully achieved, at any rate in Germany, for both a 100-h.p. rolling-mill motor and, recently, a large 800-h.p. colliery winder. The second application is the use of rectifiers on a regenerating d.c. load system, and this is of particular interest in connection with regenerative control at the present time. On certain sections of the South African Railways' system, the trains running downhill have to pump as much energy back into the substation as they have taken from the substations when going uphill. In the converting substation one unit is employed as a rectifier and another as an invertor, both being supplied from a common transformer, as only one unit is in operation at a time. I hope we shall hear a good deal more of such applications in this country too.

Mr. M. B. Sarwate (*communicated*): In spite of the fact that the ripple in the current wave has no appreciable
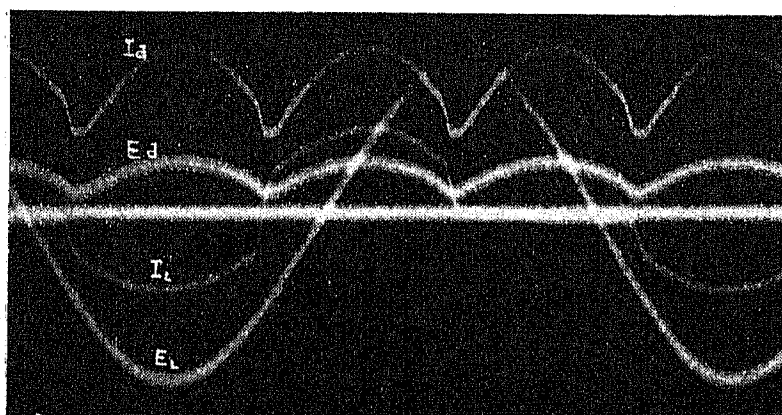
Fig. B

effect on the heating of the traction motors described in the paper, it would be extremely interesting to know whether an improvement in the wave-form could be effected without complicating the arc-transformer design and connections. The design of an efficient arc transformer is the most important factor in the manufacture of mercury-arc rectifier equipment. It would be a step forward if, by some suitable means, the arc-transformer design and connections could be simplified without sacrificing the wave-form. Such an improvement would remove the main objection to the more extensive and varied application of mercury-arc rectifiers, which is that if a power load consists largely of rectifiers the supply may have its wave-form so seriously distorted as to render its application for other power purposes practically impossible. This is all the more important in a country with a huge grid system aiming at interconnecting various power schemes. As can be easily seen from the load curves in Fig. 3 of the paper, the rectifiers carry only a small percentage of the total load. I think it is the fear of wave distortion which

limits the more extensive use of rectifiers on the London Underground Railways.

Experimental work aiming at improvement in the wave-form and simplification of the design of the arc
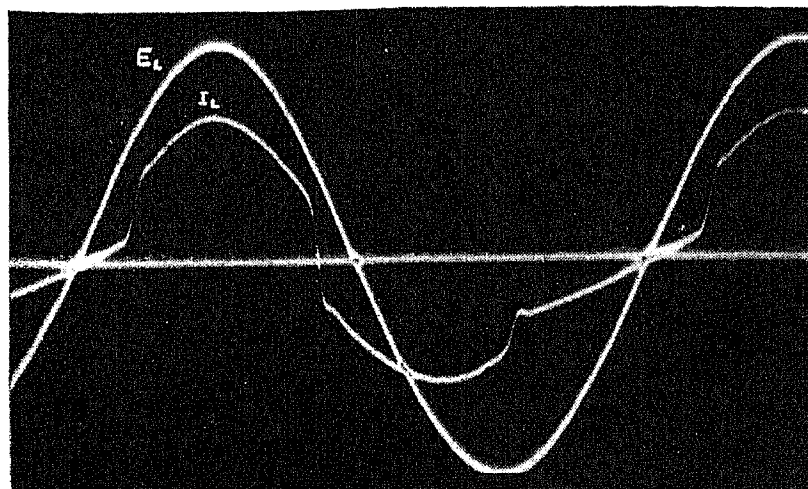
Fig. C

transformer is being carried on in the Electrical Laboratories of Liverpool University.

The curves reproduced in Figs. B, C, D, and E, obtained for two of the simplest arc-transformer connections,
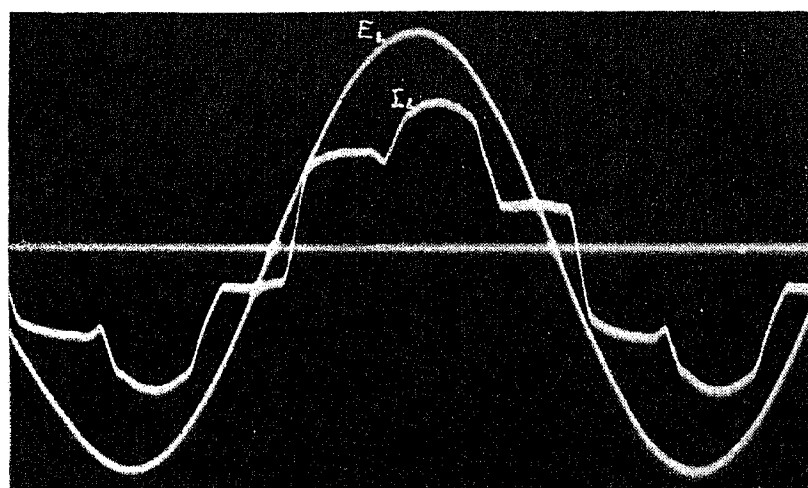
Fig. D

clearly show the possibility of improving the wave-form by the use of suitable tertiary windings. Curves E_L and I_L in Fig. B are respectively the primary line voltage and the line current of the arc transformer connected 3-phase star/interconnected-star without a tertiary winding and with a resistance load on the

d.c. side. Curves E_L and I_L in Fig. C show the supply line voltage and the line current for the same connection but with the addition of a tertiary winding, other conditions remaining the same as before. Figs. D and E respectively show similar curves for the arc transformer connected 3-phase-star/6-phase-star without and with a tertiary winding and a resistance load on the d.c. side. The less-distorted nature of the current wave-form in Figs. C and E is clearly seen. The rise in that portion of the I_L curve which indicates very nearly zero current in Fig. B is very much marked in Fig. C. Similarly the improvement in the wave-form shown in Fig. E over that in Fig. D is very noticeable.

The serious distortion of the current wave-form in the
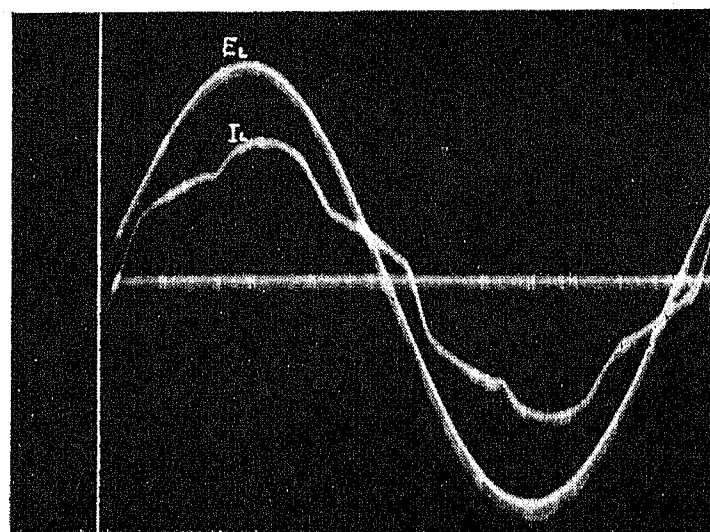
Fig. E

3-phase-star/interconnected-star connection is due to the fact that the impedance of any one phase of the primary is low for two-thirds of the whole cycle, and hence the neutral point can rotate. The same fact is perhaps responsible to a large extent for the exclusion of the straight 3-phase-star/star-connected transformer, because in such a connection the neutral may slip completely, and the current in any one phase may be periodically suppressed, particularly at very high flux densities. The use of three single-phase transformers, though quite satisfactory from an economic point of view, also involves the same danger, because in this case there is not even present the small counter-effect due to the mutual inductance always present in the normal 3-phase core-type transformer.

EAST MIDLAND SUB-CENTRE, AT LOUGHBOROUGH, 17TH MARCH, 1936

Mr. E. W. Porter: I should like to ask what is the real cause of the trouble associated with the operation of the author's rectifiers at low temperatures. I understand that in the rectifiers for the Polish Railways the makers have got over this trouble down to at least — 10° C.

I believe all the anodes mentioned in the paper are of graphite, and that the use of metallic anodes has been abandoned. In the discussions on this paper at other meetings it has, however, been mentioned that metallic

anodes are giving satisfactory results, and that in the event of backfires or heavy overloads on the rectifier it can be re-connected to the busbars more quickly with metallic anodes than with graphite, perhaps because the anodes of the latter material are incandescent under these conditions.

I think that the closed cooling system has a great advantage over the open one where corrosion is liable to be set up. In addition, closed circuits are not likely to be subject to trouble arising from dirty water or from

deposits, which may not be detected until a breakdown is experienced.

Mr. B. Nuttall: The author is responsible for a sub-station system without parallel in this country. We in this district have to be satisfied with small substations of about 500-kW capacity.

I should like to ask for what kW capacity the author would install a steel-tank rectifier in preference to the glass-bulb type, for trolley-bus service.

I notice from the substation layouts the almost entire absence of oil; air-blast power transformers are employed, and the pot type of oil circuit-breaker is adopted for the 11 000-volt switchgear. I assume that this has been purposely arranged, to minimize the fire risk due to the burning and spraying of oil.

Another point I should like to query is the method of running the system. Are the substations fully automatic in operation? For instance, what would be the effect of a high-tension " black-out " on a substation in which rotary convertors are run in parallel with rectifiers? I suggest that when the supply was restored the rectifiers would be excited first and would try to snatch the load. Perhaps the author would explain what would happen in these circumstances.

Mr. M. O. Owens: Does the author use supervisory control or multi-core pilots for the control of the circuit breakers? If pilots, how many cores does this system necessitate?

In Fig. 15 the characteristic of the rectifier between no load and 100 amperes is not shown. Is there a very big voltage-rise on this part of the characteristic? I have observed a very high voltage to be usual at no load, and also at very light loads, on glass-bulb rectifiers in traction service. This has caused some difficulty due to

the burning-out of coils in control gear and other apparatus which is necessarily continuously energized.

Mr. J. F. Driver: I should like to ask the author what is the smallest current that will suffice to maintain the arc in one of his rectifiers. For example, if the load happened to drop to, say, 5 amperes, would the arc continue to function?

There are many who would like to know what actually occurs during backfires. I understand that the makers now claim that they can produce backfires " artificially," and I should be glad to know whether oscillograms have been made to investigate the phenomena.

I believe the rectifier tanks are made of a special grade of iron, electrically welded. Has the author had any trouble with welding rot, or the percolation of the mercury through the iron?

Finally, have grid-controlled rectifiers been tried, or is the use of such apparatus contemplated?

Mr. R. G. Payne: When showing his slide of the Leicester Square substation the author said that the cooling water was kept moving only by natural circulation, and yet a minute later he stated that there was a pump for handling the water. Is this an accelerator pump?

Mr. C. A. Brearley: I should like to ask which is the better of the two transformer arrangements shown in Figs. 9 and 10 respectively. Also, is the 12-anode 6-phase system used in preference to the 12-phase system on account of the greater convenience of the transformer or for other reasons? Of what type is the surge arrestor illustrated on the left of the diagrams, and are surge arrestors used on the trains? Has any trouble been experienced in consequence of denudation of impregnating material at the top of the high-voltage cables where these have a very long drop at deep shafts?

THE AUTHOR'S REPLY TO THE DISCUSSIONS AT LONDON, NEWCASTLE, BIRMINGHAM, MANCHESTER, LIVERPOOL, AND LOUGHBOROUGH

Mr. A. L. Lunn (*in reply*): In view of the number of speakers who have taken part in the various discussions, it is proposed in this reply to make reference to individuals only where necessary for the avoidance of repetition. The points raised will be grouped as far as possible according to the arrangement of the main sections of the paper, and by this means it is hoped that those who have asked for further information in respect of any particular part of the installations described will be enabled more easily to locate the answers to their questions.

(1) Description of System
E.H.T. Distribution.

Replying to an inquiry as to the reason for the provision of the 11 000-volt $33\frac{1}{3}$-cycle cable connecting Russell Square substation to Southgate and all intermediate rectifier substations on the Northern Extension of the Piccadilly Line, the object of this was to make available along the tunnel sections an auxiliary power supply, independent of the main 50-cycle power supplies imported at Wood Green switch-house. At each of the substations concerned the auxiliary supply cable is looped-in to metalclad switchgear, which is located on the breaker gallery (indicated in Fig. 6 as " $33\frac{1}{3}$-cycle h.t.

switchgear "); a feed is taken from this point to the $33\frac{1}{3}$-cycle lighting transformer, the l.t. side of which is connected, via a manually operated circuit breaker, direct to the 440-volt $33\frac{1}{3}$-cycle supply busbars.

The $33\frac{1}{3}$-cycle auxiliary l.t. supply is utilized mainly in connection with tunnel ventilation and platform lighting, and also for substation lighting, security against the possibility of a total failure of such essential services being obtained by means of connecting half this load to the 50-cycle and half to the $33\frac{1}{3}$-cycle l.t. mains.

At Wood Green, advantage is taken of the opportunity afforded of providing a 220-volt $33\frac{1}{3}$-cycle alternative operating supply, which, by means of an arrangement of selector contactors, is automatically connected to the control-room operating busbars in the event of a total failure of the main incoming 50-cycle supplies to the switch-house; thus rendering possible, under such circumstances, the operating of any desired circuit before conditions of supply are again restored to normal.

Feeder Protection.

In answer to inquiries that have been made regarding the system of protection employed on the high-voltage mains, this has been found to be entirely satisfactory in operation, the maximum number of radial feeders in

series not being such as to preclude satisfactory time grading with proper discrimination and sufficiently rapid disconnection of a faulty feeder.

Replying to Mr. Mather, it was not necessary to install any modified form of protection for those groups of substations that appear, from Fig. 1, to be fed from ring mains, since it was not intended that the interconnectors in such cases should remain permanently in service; the sole object of the additional cable in each instance is that of enabling an alternative supply to be given from one substation to another when desired.

Substation Remote Control.

The statistics put forward by Mr. Fairburn regarding the operation of a system of supervisory control, in service in the United States, are of great interest, and indicate the very high degree of reliability that may now be expected from supervisory control equipment.

Multi-pilot control was adopted in connection with the installations under discussion, since it was considered that such a system, with its freedom from complications in the form of delicate relays, etc., would give maximum reliability in service with a minimum of attention; this view has, moreover, been entirely justified by the successful operation of the equipment during the past few years.

In regard to possible future remote-controlled installations on open sections of the railway, however, it is probable that further consideration will be given to the advisability of utilizing some form of supervisory control, since there would appear to be no doubt that recent developments have been such as to improve the reliability of this type of equipment to a standard comparable with that of the simpler but more costly multi-pilot system.

Replying to Mr. Owens, remote control of the rectifier substations by means of the multi-pilot system involves the use of from 34 to 87 wires, according to the equipment of the particular substation considered; allowance has been made for future requirements, by the inclusion of additional wires in the pilot cables—60, 85, or 96 wires being provided in different cases. As stated in the paper, two pilot cables are taken to each substation from the control point—the three combinations employed being two 30-core, one 37-core, and one 48-core, or two 48-core cables, as the case may be.

Loading of Substation Plant.

It has been remarked that a comparison of the figures of installed plant capacity, given in the paper, with the system total-load curve (Fig. 3) shows the peak loading of the rectifier plant to be one-third of full load and that of the rotary convertor to be two-thirds of full load. If due allowance is made for standby units, however, the approximate peak loading of the plant under the conditions illustrated is, in actual fact, of the order of 50 per cent of full load for rectifiers and 80 per cent of full load for rotary convertors.

As regards the average loading of the rectifier plant, it is found that the daily plant load-factors encountered in substations on the extreme outskirts of the system are at the present time very low, being of the order of 25 per cent, though an improvement is to be expected as development takes place in the districts concerned. In the more central districts, however, plant load-factors of 45–70 per cent are normally obtained.

(2) Description of Substations

Capital Costs.

Several speakers express disappointment that data relative to the capital costs of the rectifier substations, as regards both building and plant, have not been included in the paper. These substations were, however, constructed to meet special requirements as to layout and equipment, the plant installed including not only rectifiers but also a considerable quantity of gear required in connection with the railway signals and lighting supplies; further, the cost of substation buildings is largely influenced by local conditions and considerations of probable future developments, being subject to very appreciable variation according to the particular circumstances of each individual case. In view of these facts, it is clear that information relating to the capital costs per kilowatt of plant installed in the substations would be of little service in giving an indication of the cost of a simple rectifier substation, and no useful purpose would therefore be served by the publication of such figures.

As regards the capital cost of a 600-volt $33\frac{1}{3}$-cycle rectifier equipment, this is at present about equal to the cost of a 600-volt rotary convertor of the same frequency and output. I am, however, of the opinion that, once development charges have been covered, the cost of the rectifier should be appreciably lower than that of the rotary convertor.

Building and Plant Layout.

Surprise is expressed by certain speakers at the size of the substation buildings; and it is suggested that much floor space would have been saved, and considerable economies in building costs therefore rendered possible, had there been a closer spacing of the apparatus installed. This is undoubtedly the case, and had it not been desired to make ample provision for future development a more compact layout would certainly have been adopted. It must be remembered, however, that the constant and rapid development of the loads on the Underground Railways system makes it essential that all new substations shall be so constructed as to facilitate the later installation of additional plant, or of units of considerably greater capacity than those installed at the outset, and the rectifier substations under discussion were therefore designed with this object in view.

Had it been possible to locate the rectifier transformers outside the substation buildings, a considerable saving in building costs would undoubtedly have resulted. Such an arrangement was not feasible, however, in view of the decision to equip the rectifier substations with air-blast type transformers.

Regarding the desirability of the provision of cable basements in the substation buildings, there would seem to be some divergence of opinion. On the Underground Railways the extensive experience that has been gained in the maintenance of substations in which no such provision is made, has led to the definite conclusion that additional expenditure on adequate cable basements is

amply justified by the resulting simplification of the cable layout, and the consequently greater ease of inspection and maintenance.

It is pointed out during the course of the discussions that no mention is made in the paper of the means provided for ventilation in the substations. Artificial methods are not employed; adequate louvres are provided, and the natural ventilation has been found to be quite sufficient under the worst summer conditions yet encountered. Air for the recooler and transformer blowers is drawn from the basement, and is not taken direct from outside the building.

In reference to Mr. Bonner's comments on the construction of the rectifier enclosures, no trouble has been experienced due to the presence of vermin in any of the rectifier substations. Whilst it is true that expanded-metal screens give a certain degree of added protection against such nuisance, it is open to doubt whether, even by the provision of such means, it would be possible entirely to exclude vermin from the rectifier enclosures in those localities where such troubles are liable to be encountered.

E.H.T. Switchgear.

The employment of metalclad e.h.t. switchgear instead of cellular-type gear is advocated by Mr. Davies as a means of economizing in floor space, and thus of obtaining a more compact substation layout. Though it cannot be denied that metalclad gear has many advantages, a serious objection to its use is that mentioned by the speaker himself, namely the inaccessibility of connections, etc. Failures in gear of this type are admittedly infrequent, yet it is clear that should trouble eventually occur for any reason, then the general inaccessibility may lead to excessive delay both in locating and also in repairing the fault.

The great advantage of cellular-type gear is the ease with which every part can be inspected, and the rapidity with which faults can be rectified; for this reason it is employed as the standard form of e.h.t. equipment in the Underground Railways substations, long experience having shown that in properly-designed equipment the risk of trouble due to flashover is negligible.

Dr. Miller refers to the busbar surge-arrestors, suggesting that these would have given better service had they been connected in front of the feeder circuit-breakers. While I am aware that such would have been a more orthodox arrangement, I do not consider that the degree of added protection that might have been obtained by its adoption would have been of sufficient importance to outweigh the advantage of the existing scheme, which permits of maximum simplification of the e.h.t. layout.

D.C. Switchgear.

In reply to comments regarding the arrangement of the d.c. switchgear, it was not considered necessary to enclose each breaker within protective barriers, as sufficient space was available on the gallery to permit of adequate clearances between adjacent circuits.

Movable shields are provided by means of which the copper-strip connections rising through the gallery floor to each breaker may be completely enclosed whilst work is being carried out in the vicinity, and there is ample room for work to be carried out on any breaker without risk of accidental contact with live apparatus.

Substation Control Transfer Contactors.

Answering Mr. Rawll, arrangements in the rectifier substations are such that the e.h.t. busbar-section switches normally remain closed, only one incoming feeder being on load.

The substation control transfer contactors to which reference is made in Figs. 9 and 10 are included with the main object of preventing accidental paralleling of the incoming feeders via the substation control transformers, should it become necessary at any time to open the busbar section switches and to arrange for each section of the busbars to be supplied independently by one feeder.

Rectifier Overload Protection: Interlocking of Breakers.

As assumed by Mr. Rogers, there would be little object in providing the rectifiers with d.c. overload circuit breakers, since the overload protection afforded by the track-feeder circuit breakers is quite adequate.

The rectifier positive breaker, therefore, is arranged to operate only on reverse current, and has the primary function of isolating the rectifier from the d.c. system in the event of backfire.

Regarding the arrangements for a.c. overload protection of the rectifiers, suitable provision is made in the equipments of both types under discussion, to ensure that in the event of a backfire the faulty rectifier will be disconnected from the e.h.t. supply practically instantaneously and quite independently of the action of the inverse time-delay overload relay. In the case of the Western Extension equipments, this effect is secured by means of a direct-operating overload tripping device fitted to the rectifier a.c. breaker, and adjusted to operate under heavy fault conditions only; the method employed on the Northern Extension, however, is that of interlocking the rectifier a.c. breaker with the high-speed breaker, so that tripping of the latter must cause the simultaneous opening of the former.

The foregoing remarks also serve as an answer to those speakers who inquire as to the reason for the difference in the arrangement of interlocking between the a.c. and d.c. breakers of the Northern Extension and Western Extension rectifiers respectively; clearly, the provision of full interlocking becomes unnecessary when an independent tripping device is provided on the a.c. breaker. I regret that in the paper no reference was made to this point.

There seems to be little to choose between the two systems of protection as far as effective operation is concerned, though the direct tripping overload feature of the Western Extension equipments is certainly the more positive in action, no reliance being placed upon interlock contacts which may possibly fail at a critical time. On the other hand, the employment of full interlocking between a.c. and d.c. breakers eliminates the necessity for the introduction of an additional time-delay relay which, otherwise, must be provided for the purpose of preventing the high-speed breaker from reclosing immediately after tripping on a fault of insufficient magnitude to cause instantaneous opening of the a.c. breaker. The

inclusion of this additional relay accounts for approximately 5 seconds of the total time required to start up a Western Extension rectifier.

Mr. Cox, in reference to the respective systems of interlocking, remarks that a disadvantage of full interlocking, as applied to the Northern Extension equipments, is that it precludes the possibility of keeping the a.c. breaker closed for the purpose of running the cooling blowers, should a transformer or a rectifier become overheated. This criticism does not apply, however, as the transformer over-temperature relay, in operating, itself causes the equipment to be locked out; since it would be undesirable to permit the re-connection of an overheated transformer to the e.h.t. busbars before the cause of the failure had been investigated. In the event of the overheating of a rectifier, although the transformer is disconnected and the recooler blower is shut down owing to the interlocking of the breakers, it is still possible to accelerate the cooling of the tank by running the circulating-water pump, which is supplied from the substation control busbars.

(3) Description of Rectifier Equipments
Rectifier Tank.

Dealing with the comments of Mr. Henderson and Mr. Bonner regarding the use of steel anodes in recently-constructed rectifiers, I would draw attention to the fact that the reference made in the paper to the relative merits of steel and graphite anodes respectively is clearly specified as being a quotation of the claims made by the manufacturers of the particular rectifiers under discussion; no experience of the operation of rectifiers provided with steel anodes has been obtained on the Underground Railways, and no comparison of such plant with rectifiers supplied with graphite anodes can therefore be given. It is believed, however, that both in this and in other countries the majority of the manufacturers of steel-tank rectifiers favour the use of graphite anodes.

Further information is requested regarding the methods employed on the rectifiers for the sealing of the vacuum joints other than those at the anodes, which are described in the paper. In the case of the Western Extension rectifiers the cathode seal is of the mercury type, whilst the main vacuum joint, i.e. between top plate and vacuum tank, is in its essentials a plain " lip and groove " joint, the sealing medium employed consisting of a lead gasket, on which the " lip " of the joint is bedded. Northern Extension rectifiers are provided with mercury sealing of all vacuum joints.

One speaker expresses the view that both the types of rectifiers under discussion are obsolete in design. Nevertheless, the performances of both the Northern Extension and the Western Extension rectifiers would appear to compare very favourably with the reported performances of other rectifiers of different make.

Ignition and Excitation.

Replying to inquiries as to the relative merits of the systems of ignition provided on the Northern Extension and Western Extension rectifiers respectively, it may be stated that up to the present time no appreciable difference in reliability or effective operation has been found

to exist between the two systems. Nevertheless, in my opinion d.c. ignition is to be preferred. In starting up a rectifier the striking anode of which is supplied with direct current, only one operation of the ignition mechanism is necessary for the establishment of the ignition arc; if the rectifier is equipped with a.c. ignition, several attempts are frequently necessary before the striking anode finally makes contact with the cathode at the required instant to enable the ignition arc to be correctly struck. Some degree of additional wear and tear of the mechanism must therefore result from the employment of the a.c. system of ignition, and this may tend to lead ultimately to increased rectifier maintenance charges, particularly in those cases where springs are employed for the purpose of controlling the movement of the striking anode. As regards the maintenance required by the small motor-generator set or auxiliary metal rectifier employed in conjunction with the d.c. system of ignition, this is so small as to be completely negligible.

Regarding the matter of rectifier excitation, Mr. Calverley—who, it is noted, himself favours the d.c. system of excitation—points out that the 6-phase system involves the provision of an unnecessarily large number of vacuum seals in the rectifier top plate. I am inclined to agree with this view, though it must be emphasized that the additional excitation anode seals on the Northern Extension rectifiers have given rise to no inconvenience in operation. The chief advantages claimed for the 6-phase system are those of easier starting and greater stability of the main arc, together with an increased immunity of the rectifier from backfire. Under certain conditions of operation it is probable that these claims are justified, but conditions in the substations under discussion are such that there is no discernible difference between the general stability of rectifiers having single-phase excitation and those having 6-phase excitation. It can only be stated, therefore, that the two systems of excitation have been found to give equally satisfactory results.

Vacuum System.

Replying to Mr. H. Rissik, it has not been found to be necessary, on either type of rectifier under discussion, to make provision for automatic low-vacuum control of the rotary vacuum pump. Such an arrangement was at first adopted on the Western Extension equipments, but with indifferent success; as stated in the paper, a vacuum bus-pipe was therefore installed in each Western Extension substation, the new arrangement being such that a rotary vacuum pump continues to evacuate the bus-pipe as long as there is a rectifier on load in the substation. When all the rectifiers are shut down, however, evacuation of the bus-pipe ceases, the rotary vacuum pump stopping automatically as the last rectifier is taken off load.

In answer to Mr. Coke's inquiry, these vacuum bus-pipes have given entirely trouble-free operation since the time that they were installed.

On the Northern Extension the rotary vacuum pump of each rectifier runs only when the rectifier is on load—commencing to run at the beginning of the starting sequence, and thereafter running continuously until the

rectifier is again shut down. Operation of the pump whilst the rectifier is standing-by has not been found to be necessary, owing to the ample capacity of the inter-stage chamber.

Transformers.

The employment of rectifier transformer banks consisting of three single-phase units has the advantage that, in the event of a transformer failure, the removal of a faulty unit and its replacement with a spare can be effected with greater ease and, therefore, greater rapidity than is possible in those cases where 3-phase transformers are utilized.

Since the use of single-phase transformer units tends to introduce difficulties from the manufacturers' point of view, however, it has been decided not to continue with this practice, and, as stated in the paper, 3-phase transformers will be provided for rectifier equipments at present being installed in new substations on the Underground Railways.

In reply to inquiries concerning the transformer cooling arrangements, oil cooling is not provided, the transformers both of the equipments under discussion and of the new equipments mentioned above being of the simple air-blast type; filtering of the cooling air has not been found to be necessary. It has been the standard practice in the past to employ transformers of this type in all the Underground Railways installations, since it is considered that extended fire risks are thereby reduced to a minimum. I am unable to agree with Dr. Garrard that oil-immersed transformers are safer than the air-blast type.

Reference is made to the fact that bake-out windings are provided on Northern Extension but not on Western Extension rectifier transformers, and further information is requested in this connection. Little comment is possible; the method to be adopted for the supply of current for bake-out purposes was not laid down in the specification, and the manufacturers of the Western Extension rectifiers elected to provide a portable bake-out transformer, for use in all substations on the section, in preference to the alternative scheme of providing special bake-out windings in the rectifier transformers.

From the point of view of convenience in operation, there can be no doubt that of the two schemes the latter is much to be preferred, since not only is the necessity for transporting heavy equipment from substation to substation eliminated but the actual work of connecting up, etc., is facilitated. The increased complication of the rectifier transformers may perhaps be regarded as a disadvantage of the scheme, but provided that the additional windings can be included without risk of impairing the reliability and performance of the transformers (as would appear to be the case, from the experience gained with the Northern Extension transformers), this is a matter which affects the manufacturer rather than the user.

In answer to an inquiry regarding the protection of the transformer secondary windings against high-voltage surges, no use has yet been made of auto-valve surge-arrestors. On Northern Extension equipments the simple horn-gap and resistance type of arrestor is employed, whilst Western Extension equipments are provided with arrestors of the ordinary multi-gap type.

Surges of 5 kV have been measured by means of a klydonograph, connected across the transformer surge-arrestors of a Western Extension equipment operating under conditions of low temperature. Disturbances of this nature, of course, vary in severity according to the circumstances under which they occur and the characteristics of the particular circuit concerned, and it is believed that, under certain conditions, surge voltages of appreciably greater magnitude than that indicated above are liable to be encountered.

In reply to a request for a comparison between the types of transformer connections employed on the Northern Extension and Western Extension equipments respectively, it may be stated that the principal advantage claimed on behalf of the star/double 6-phase diametric connection (Fig. 10) is that by its adoption the necessity for an interphase transformer is avoided. The working of this arrangement, which is suitable for use only in those cases where the rectifier transformer is composed of single-phase transformer units, is outlined by Mr. Gallizia (page 144), who also emphasizes that, were a 3-phase type of rectifier transformer to be connected in this manner, bad voltage regulation and power factor would result. By comparison with the delta/double-star double 6-phase connection with interphase transformer (Fig. 9), the star/diametric connection of single-phase units gives similar utilization of the transformers, but a slightly worse voltage regulation between light load and full load; the transition load (i.e. the load current necessary to reduce the rectifier no-load d.c. terminal voltage to normal line value) is considerably higher in the absence of an interphase transformer, the total losses in the rectifier loading-resistance therefore being increased to some extent. No comparative figures of core loss are available, but it is believed that the triple-frequency flux produced in the transformers when the star/diametric connection is employed results in somewhat higher losses than those occurring in transformers connected in delta/double-star, since in this latter case triple-frequency fluxes are almost entirely eliminated from the main transformers—being present only in the core of the interphase transformer, which is much smaller and works at a much lower density. Of these two types of connections, the delta/double-star double 6-phase arrangement with an interphase transformer is the more commonly employed in conjunction with 6-phase 12-anode rectifiers.

As surmised by Mr. Brearley, the principal reason for the adoption of double 6-phase in preference to 12-phase operation, was that of the desirability of obtaining maximum simplicity in the rectifier transformers. The 12-phase system has undoubted advantages in giving an improved wave-form of the current drawn from the a.c. mains, and a reduced ripple in the rectifier output voltage. It may be of interest to note, however, that all 12-phase connections suffer from the common disadvantage that, due to the small voltage-difference between successive phases during the working period, the arc is, on occasion, liable to miss a phase; a tendency therefore exists towards instability of the rectifier output voltage and reversion to 6-phase operation.

Frequency Change-Over.

Owing to the necessity for maintaining the voltage regulation of a rectifier equipment within the desired limits, the reactance of the rectifier transformer must be reduced to the minimum value consistent with safety under conditions of short-circuit or backfire. It would therefore have been impossible to provide against the necessity for rewinding the transformers of $33\frac{1}{3}$-cycle equipments in the event of a change-over to 50-cycle operation, by further reducing at the outset the transformer reactance in the manner suggested by Mr. Rawll; had this been attempted, operation at $33\frac{1}{3}$ cycles would have been rendered unsafe, and the voltage regulation of the equipments if operated at 50 cycles would still have been excessively bad.

Regarding the effect on the smoothing circuits of a rectifier should the equipment be changed over from one frequency of operation to another, Mr. Field is correct in his assumption that re-tuning of the resonant shunts would be necessary.

In a $33\frac{1}{3}$-cycle rectifier equipment provided with full smoothing circuits, five resonant shunts are utilized, tuned for frequencies of 200, 400, 600, 800, and 1 000 cycles respectively. The same equipment converted for operation on a 50-cycle supply would require four resonant shunts, tuned for frequencies of 300, 600, 900, and 1 200 cycles.

(4) Performance

Efficiency.

The respective efficiency values included in Table 2 refer to a rectifier now in service at Barons Court sub-station and a rotary convertor in service at Acton Town substation, and are the result of tests carried out by the manufacturers of the Northern Extension rectifiers, at their works. I am assured that the greatest care was taken to eliminate the possibility of error due to causes such as those outlined by Dr. Rayner, and it is believed that full reliance may therefore be placed on the results as published.

Dr. Rayner's curves (Fig. A) show a very interesting comparison between the respective performances of British- and German-built rectifiers; no mention is made, however, of the type of transformer cooling employed in the latter case. In this connection, it may be pointed out that the characteristic of the British rectifier would have been raised by about $\frac{1}{2}$ per cent had oil-cooled instead of air-blast type transformers been provided.

Replying to Mr. Bonner, the auxiliaries form an integral part of the whole rectifier equipment and without them the rectifier could not be put into operation; it cannot be agreed, therefore, that the auxiliary power requirements of a rectifier should not be taken into account in estimating the overall efficiency of the plant. As regards the values given in Table 2, the power required by that apparatus purely associated with the remote control of the rectifier was not included in the calculations, as the rotary convertor was arranged for manual operation; since both the rectifier and the rotary convertor were provided with air-blast type transformers, however, account was taken, in each case, of the power supplied to the transformer blower.

I am unable to appreciate the point of Mr. Johnson's criticism that it is unfair to compare the respective efficiencies of 630-volt $33\frac{1}{3}$-cycle rectifiers and rotary convertors. It is well known that the efficiency of the rectifier improves as the d.c. voltage of operation is increased, but this hardly applies to the case in point; the plant under discussion was required for operation on a 630-volt system, and the tests were therefore carried out on 630-volt units. Similarly, with very few exceptions, the rotary convertors in service on the Underground Railways are supplied with power at $33\frac{1}{3}$ cycles, and it would appear to be reasonable, therefore, in making comparisons of the nature indicated in the paper, to select for this purpose units designed for operation at the frequency of the system.

Replying to Mr. Wood, the arc deflectors attached to the anodes of Western Extension rectifiers are not found to give rise to any increase in the arc voltage-drop with consequent reduction in efficiency.

Power Factor: A.C. Harmonics: Interference.

Little difference has been observed in the system power factor since the addition of the rectifier load. Such lagging effect as has occurred must be looked upon as beneficial, however, since a problem formerly experienced on the system was that of overcoming a tendency towards a leading power factor—with consequent risk of unstable operation of the alternators under certain conditions of loading. In general, the operating power factor of the system is practically unity.

Dr. Garrard suggests that the installation of a synchronous condenser might be a suitable method of avoiding the necessity for de-rating the generators, should the system power factor tend to deteriorate unduly as a result of future increases in the ratio of total rectifier load to the total system load. It is agreed that by such means the purely reactive kVA taken by the rectifier plant could be reduced or entirely eliminated if desired. At the same time it is pointed out that the harmonic power component, which in its effect on the generators may be regarded as being equivalent to an increase in total reactive kVA, would remain unaffected by the operation of a synchronous condenser of conventional design. As stated by Mr. H. Rissik, during the course of the discussion at Liverpool, in order to correct for the total harmonic power component it would be necessary to utilize a machine generating harmonics equal in magnitude and frequency but opposite in phase to those produced by the rectifiers.

The oscillograms brought forward by Mr. Sarwate, illustrating the improvement in wave-form obtained by the use of tertiary windings on rectifier transformers, are of great interest, and I agree that any improvements leading to the simplification of rectifier transformers and the reduction to an absolute minimum of the harmonics introduced into the supply system by rectifier operation, would be of considerable importance.

Mr. Sarwate is incorrect in suggesting that fear of voltage-wave distortion has tended to limit the utilization of rectifier plant on the Underground Railways. It is believed that a substantial increase will be possible in the total rectifier load on the system before the voltage wave-form is affected to any marked extent.

So far as the loading of the rectifier plant is concerned,

this is obviously dependent only upon the demands of the railway sections concerned. Owing to the disposition of the substations on the system the proportion of the total rectifier load to total system load cannot be varied to any appreciable extent by transferring load from the rectifiers to the rotary convertors, or vice versa; this will be seen quite clearly by referring to Fig. 1. It would therefore be impossible to make any experiment of the nature suggested by Mr. Watson-Jones, to determine the effect on the system-voltage wave-form of any heavy increase in the proportion of rectifier load supplied.

In connection with the inquiry made by Mr. Gibson regarding the utilization of dissimilar transformer connections on the respective rectifiers in a substation, it is believed that a scheme of this nature would have definite advantages, since, provided that suitably matched transformer connections were used in conjunction with 6-phase rectifiers of equal output, not only would the resultant wave-form of the current in the a.c. feeders approximate to that corresponding to 12-phase operation, but there would also be a similar reduction in the magnitude of the harmonic currents appearing in the d.c. system. It may be mentioned that a very clear explanation of this method of obtaining a reduction in both a.c. and d.c. harmonics in rectifier circuits is given in a recently-published work on the mercury-arc rectifier.*

When star-connected and delta-connected equipments respectively are installed in different substations, as is the case on the Underground Railways, a reduction is obtained in the resultant harmonics in the generators, but there is no reduction of harmonics in either the a.c. feeders or in the d.c. system.

Referring to the divergent opinions voiced in the discussion regarding the necessity for the installation of smoothing equipment in rectifier substations, I have little to add to my statement, made in the paper, that on the Underground Railways such provision is considered to be desirable in order that added security may be obtained against the possible occurrence, at any time, of interference troubles.

Doubt is expressed as to the utility of a d.c. reactor when employed by itself without the addition of resonant shunts. In the absence of test data, I am unable to give any definite indication of the degree of smoothing produced by the reactors on the Western Extension equipments, but I agree that this may be small by comparison with the smoothing effect of the inductive loop formed by the current rails.

In reply to Mr. Bonner, telephone cables—but practically no exposed telephone wires—run parallel with the a.c. feeders over considerable distances, both in the running tunnels and on open sections of the railway. I would point out, however, that on systems where distribution is by means of 3-core cable the risk of interference due to harmonic currents on the a.c. side is very small, the magnitude of the resultant external field produced by the a.c. feeder currents then being reduced to a minimum.

Regulation.

Replying to Mr. Henderson, I regret that in the advance copies of the paper the specified voltage regu-

* H. RISSIK: "Mercury-Arc Current Convertors" (Pitman, 1935).

lation of the rectifier equipments under discussion was incorrectly stated to be $4\frac{1}{2}$ per cent; this figure was corrected for the *Journal*, however, the actual value specified being $3\frac{1}{2}$ per cent from 1/10th to full load. The regulation voltage-drop of 31–38 volts obtained in practice, has not been found to give rise to any inconvenience in operation.

Dealing with Dr. Jakeman's inquiry regarding the voltage characteristics reproduced in Fig. 15, reactance in any part of the whole rectifier circuit tends to delay the process of commutation of the load current from anode to anode, and therefore to reduce the average d.c. voltage available at the rectifier terminals. It follows that, for any given conditions of loading on the rectifier, the d.c. output voltage will vary if the total reactance in circuit with the rectifier is varied; over the whole range of loading some displacement of the voltage characteristic of the unit will therefore occur should changes be made in the reactance of the supply system. It is obvious that such a change in total reactance is brought about each time that the number of alternators feeding the system is increased or decreased, and Fig. 15 illustrates the resultant effect on the rectifier voltage characteristic in the particular case under consideration.

As regards the methods indicated in the paper as having been adopted for controlling the no-load voltage-rise characteristic of both types of transformer connections employed on the rectifier equipments under discussion, this matter was left entirely to the discretion of the manufacturers.

It is not believed that the losses entailed by the use of loading resistances are much in excess of those that would have resulted had any other system been adopted, such as separate excitation of the interphase transformer, since the resistances are in circuit for only a very short total period each day.

Replying to Mr. Owens, the no-load voltage-rise given by the delta double-star connection is about 15 per cent, that given by the star-diametric being somewhat higher.

(5) General Operation

Behaviour on A.C. System Disturbances.

Answering Mr. Irvine, no difficulty has been experienced in operating adjacent rectifier and rotary-convertor substations connected to different a.c. networks; in fact, it is probable that such a combination gives somewhat more stable operation than would be obtained, under similar conditions of supply, from adjacent rotary-convertor substations.

I am in entire agreement with the views expressed by certain speakers to the effect that the general stability of the rectifier under abnormal conditions of supply, and the greatly reduced difficulty in operating adjacent substations fed from independent sources when rectifier plant is utilized, are important advantages which under certain conditions may even outweigh considerations of efficiency. Obviously on any supply system, and particularly on a system such as that of the Underground Railways, continuity of supply is of primary importance; the added degree of security given by the rectifiers against possible interruptions due to the disturbance of plant following irregularities in the a.c. supply system

is therefore very desirable and of considerably greater consequence than a small gain in efficiency.

Restarting of Plant after Supply Failures.

It is asked whether consideration has been given to completely automatic reclosing devices, such that, in the event of a shutdown due to fluctuation or total failure of the a.c. supply, a rectifier will automatically put itself on load again as soon as conditions are restored to normal. Satisfactory trials were made of such an automatic feature, but, in view of the rapidity with which the plant can be restarted by the control-room operator, it was decided that the very small saving in time that would be effected by automatic restarting would scarcely justify the additional expenditure involved in making such provision.

In the absence of automatic equipment of this nature, the point mentioned by Mr. Nuttall in connection with the possibility of difficulty being encountered, after an e.h.t. failure, owing to rectifiers restarting more rapidly than rotary convertors installed in the same substation, does not arise; in this connection it may also be noted that only one substation on the system, namely Hendon, is equipped with both rectifier and rotary-convertor plant.

Backfire.

In reply to Mr. Driver, I am given to understand that the manufacturers of rectifier plant have made extensive research into the phenomenon of backfire, but I regret that I myself am unable to publish oscillograms illustrating the conditions obtaining in a rectifier at the instant of the occurrence of such a fault. A backfire, being essentially a breakdown of the valve action of the rectifier following upon the development of cathode spots on one or more anodes, is equivalent to a short-circuit on the corresponding phases of the rectifier transformer secondary winding, conditions being rendered more serious by the effect of the heavy resultant d.c. component, which, in causing d.c. magnetization of the transformer core, increases the maximum value of short-circuit current taken from the a.c. supply system.

Several speakers refer to the increased severity of the duty to be performed by a rectifier oil circuit-breaker under such conditions, and request information regarding the rupturing capacity of the oil circuit-breakers of the equipments under discussion. The standard-type breaker originally provided with the Hendon rectifier was rated at 150 000 kVA, and was of equal capacity and similar in all respects to that at present employed in connection with the rotary convertor operating in the same substation. Subsequent to the backfire to which reference is made in the paper, a breaker was installed of 250 000 kVA rating (an increase of 67 per cent); all other rectifiers on the system have been provided with breakers of approximately 40 per cent higher rupturing capacity than those which would have been provided for rotary convertors operating in the same substations.

Dr. Miller, in asking what refinements are responsible for the improved performance of the modern-type rectifier and for its freedom from backfires, raises a question that would best be answered by the manu-

facturers themselves, as I have had no first-hand experience with units of an earlier type than that at Hendon. It may be stated, however, that the very greatly increased reliability of the present-day rectifier is due, to a great extent, to modifications in the design of anode shields and arc deflectors, and to the greater attention that, of recent years, has been given to the problem of heat distribution; it is believed, also, that many of the difficulties experienced with the earlier types of rectifiers were due to the use of unsuitable materials in construction.

(6) Maintenance

In the course of the discussion a good deal of attention is given to the comparative maintenance required by glass-bulb and steel-tank rectifiers respectively, and Mr. Fairburn quotes some very interesting data referring to glass-bulb installations installed on the L.M.S. Railways. I do not propose to pursue this particular line of discussion, which lies somewhat beyond the scope of the paper, but I would mention that I am in entire agreement with the substance of the remarks made in this connection by Mr. H. Rissik (at Manchester) and by Mr. Read (at Birmingham).

Dr. Kahn emphasizes certain points of comparison between rotary convertors and rectifiers, and states that the case for the rectifier will be complete when the necessity for the inclusion of its various auxiliaries has been eliminated. I am given to understand that there is every prospect of this condition being at least partially fulfilled in the very near future. At the present time there is available a new type of air-cooled steel-tank rectifier which is capable of maintaining a high state of vacuum for long periods without the necessity for vacuum pumps.

Regarding Table 4, data relative to the total plant outages were not included as exact figures were not available. During the period covered by the analysis, cases frequently occurred where subsequent to a breakdown the rectifier concerned was kept out of commission for a longer period than was necessary for the repair of the defective apparatus, in order that general examination of other parts of the equipment might be effected. The principal object of the inclusion of this Table was that of illustrating the degree to which the various components of the rectifier equipments affected the reliability of the whole installation during the period considered; the number of breakdowns considered in the analysis amounted to a total of 48.

In reply to Mr. Driver, no trouble has been experienced due to the percolation of mercury through the walls of rectifier vacuum-chambers or to the deterioration of the welded joints.

Answering Mr. H. Rissik, the majority of the control-gear failures were due to the development of minor defects in that part of the rectifier automatic gear necessarily included by reason of the remote-controlled nature of the plant; there were included, however, one or two cases of faulty vacuum-gauge operation.

As regards the particular maintenance repairs mentioned in the paper, the ignition-anode failure (page 139) occurred on a rectifier in which the striking tip is locked into a socket in the striking rod by means of a grub

screw; the latter, when tightened down, is welded to eliminate the possibility of slackening due to vibration, and it is believed that stresses set up in the tungsten tip during the welding process ultimately caused fracture of the metal.

The bake-out referred to on page 139 was mentioned with the object of illustrating the serious nature of the outages that may result in the event of trouble involving the opening of the vacuum chamber of a rectifier, and is the worst case that has yet been encountered. It should perhaps have been made clear, however, that the tank was kept open for a longer time than was absolutely necessary, since it was desired to make a very complete examination of all parts of the internal assembly. It is agreed that a full bake-out may be effected within the time indicated by Mr. Henderson, but this is the case only under favourable conditions. Figures of the order quoted in the paper are liable to result should anything occur to delay the re-evacuation of the tank.

Regarding the question of vacuum gauges, it has been my experience that regular routine checking of the calibration of Pirani gauges is very desirable, if trouble-free operation is to be ensured. This work is greatly facilitated if each rectifier is provided with a permanently-connected McLeod gauge, and it cannot therefore be agreed that such provision is unnecessary, as is suggested by more than one speaker.

In connection with the rectifier circulating-water system, figures such as those requested by Mr. Fielding —showing the percentage increase in capital cost of the closed-circuit system over that of direct cooling with tap water—are not available. The Hendon rectifier is to be provided with a closed-circuit system, and it is expected that appreciable reduction in maintenance costs and water charges will result—particularly the latter.

Mr. Smith comments upon the good condition of the Hendon rectifier water surfaces, as illustrated by the slide shown by me during the discussion. In this connection it may be pointed out that a large accumulation of deposits in the rectifier water-jacket is not to be expected when direct cooling with tap water is provided, as the greater part of the sludge formed is probably carried away to waste by the cooling water.

In reply to Mr. Spencer, the cooling-water supplies to the various rectifier substations are of good quality and entirely free from the corrosive properties of such peaty waters as are commonly obtained from moorland districts; the results of an analysis of a typical water sample are as follows:—

				Parts per 100 000
Nature ..	..	..	..	Slightly alkaline
Total solids ..	..	..	..	.. 33·5
Loss on ignition (organic matter, etc.)		..		8·5
Permanent hardness	..	..	..	3·2
Temporary hardness	..	..	..	21·6
Total hardness	..	..	..	24·8
Magnesium hardness (included in temporary hardness)..		..	..	0·8
Sodium chloride	..	..	..	4·7
Conductivity (as dionic units)	..	..	440

As stated in the paper, it is believed that the excessive sludging in the cooling systems of the Western Extension rectifiers was entirely due to the presence of an unduly high percentage of dissolved oxygen in the water, and it is hoped, therefore, that this difficulty has been overcome by the elimination of the open discharge that formerly existed in the circulation systems of these units. Further investigation of this matter is, however, at present in progress, and it cannot yet be stated definitely that chemical treatment of the water will not ultimately prove to be necessary.

I am given to understand that use has been made of distilled water in certain rectifier installations, where corrosion difficulties have been experienced. Under certain conditions distilled water is itself very corrosive in action, but this can generally be overcome by the addition of a small quantity of caustic alkalinity. If this latter precaution is observed, and provided that steps are also taken to ensure that the dissolved oxygen content is reduced to a minimum, there would appear to be no reason why the use of distilled water should not prove to be very effective in eliminating corrosion troubles. On a system where the number of rectifier installations in service is large, however, the adoption of such a scheme would scarcely be desirable—by reason of the inconvenience and additional expense that would undoubtedly be involved in distributing the necessary supplies.

Answering Mr. Payne, the circulation of water through the rectifier jackets is entirely dependent upon the operation of the pump to which he refers; I did not intend my remarks to convey the impression that cooling of the rectifier was effected by means of natural circulation.

(7) Regenerative Control

I regret I am unable to give a reply to those speakers who inquire the attitude of the Board towards the adoption of regenerative control on the Underground Railways, and the effect that such a policy would have upon the future development of rectifier substations on the system, since these matters are at present under consideration.

In reference to the trolley-bus system, Mr. Neal inquires as to the working of the regenerative braking in view of the fact that the system is supplied from rectifier substations which cannot absorb the regenerated power. Under normal conditions, when a trolley-bus regenerates, the power is returned to other vehicles in the same section, or, failing this, to vehicles in adjacent sections (via the substation busbars). In the event of a complete absence of demand for this power an over-voltage relay which is included in the trolley-bus equipment operates to disconnect the equipment from the trolley lines and to connect a loading resistance across the regenerating motor, thus producing a rheostatic braking effect.

(8) Grid-Controlled Rectifiers

Regarding the possible use of grid-controlled rectifiers on the Underground Railways, it is too early to forecast future developments, but there would seem to be little reason to expect that grid control will be adopted unless in conjunction with regeneration.

Mr. Vandersyde is referred to the remarks made by Mr. Whitaker, at Birmingham, for the answer to his

question in connection with the possibility of eliminating rectifier auxiliary breakers by the employment of grid control. As regards Mr. Vandersyde's second inquiry, I regret that I am not in a position to discuss the probable trend of future developments in high-voltage circuit-breaker design.

(9) General

Replying to Mr. Watson-Jones, trials have been made in the past, in rotary-convertor substations, of protective devices designed to limit to safe values the surge voltage liable to result in the d.c. system from the occurrence of severe d.c. faults. This matter is still under investigation, however, and no equipment of a similar nature has been provided in the rectifier substations.

The earthing device shown in Fig. 9 between the rectifier negative connection and the earth-leakage relay, is included with the main object of ensuring immediate disconnection of the rectifier in the event of a breakdown of insulation between primary and secondary windings of the main transformer.

Regarding the variation of rectifier tank potential mentioned by Mr. Calverley, the value of the potential at any given time depends upon the conditions then obtaining in the d.c. system; the minimum value under normal circumstances is approximately 500 volts to earth, the maximum value being about 580 volts to earth.

In answer to Mr. Driver's query as to the smallest current that will suffice for the maintenance of the rectifier main arc, it is claimed by the manufacturers that a voltmeter current is sufficient for this purpose. It is pointed out, however, that in the case of the plant under discussion, the use that is made of loading resistances for the purpose of automatically controlling the no-load voltage-rise, eliminates the possibility of the rectifier load current falling below a definite fixed value considerably in excess of that at which the main arc is liable to be extinguished.

Replying to Mr. Varley, the high-voltage cables passing down the vertical shaft at Leicester Square substation are of the plain lead-covered type without armouring and are supported at 8 ft. 4 in. centres by means of cast-iron cleats of normal design, suitable lead liners being placed round the cables to prevent damage to the sheathing. No further anchorage of any description has been found to be required.

In cases where e.h.t. cables of the double-wire armoured type are employed, e.g. on the Northern Extension in the Manor House and Wood Green shafts, advantage is taken of the opportunity of utilizing cone-type suspenders of the usual pattern, the arrangement being such that the whole weight of the cable is carried by the armouring. Below these suspenders steady cleats are fixed at approximately 7 ft. spacing.

As regards Mr. Brearley's inquiry, no difficulty has been encountered at any time due to the migration of impregnating compound from the insulation of the upper sections of high-voltage cables suspended in deep shafts. The class of cable employed is insulated with paper impregnated, before application to the conductors, with a form of compound that retains a high viscosity at normal working temperatures.

I am disappointed to find that, in his general reference to the future development of rectifier plant for 600-volt operation, Mr. Whitaker is not very optimistic as regards the prospects of reduced size and costs for given output.

Mr. Peck is a firm supporter of the rotary convertor, and I agree that the rotary-convertor plant in service on the Underground Railways has set an extremely high standard in regard to reliable operation over long periods. In this connection it may be of interest to note that a considerable number of rotary convertors at present in service on the system were first put into commission in 1905, and will undoubtedly be capable of satisfactory service for many years to come. Certain of these machines were originally designed for operation on a 25-cycle supply from the old Central London Railway power house at Wood Lane, but a frequency change-over (completed in 1928) was later effected, whereby the whole of the Central London Railway was supplied at $33\frac{1}{3}$ cycles from Lots Road power house. The machines were suitably reinforced for the higher running speed, and have continued to give very satisfactory service throughout.

Nevertheless, in view of the fact that a rectifier is a static machine, and bearing in mind the high quality of the service given by the rectifier plant under discussion during its relatively short period of operation, I feel sure that such plant is likely to have a useful life at least equal in duration to that of rotary-convertor plant.

Acknowledgments

THE MEASUREMENT OF LARGE SUPPLIES OF ELECTRICAL ENERGY FOR COSTING PURPOSES

By W. CASSON and A. H. GRAY, M.Sc., Associate Members.

SUMMARY

The authors suggest in the Introduction that, for large supplies of electrical energy, an accurate estimate should be made of their cost to the supply authority, so that comparison can be made with the actual charges, to check the accuracy of the tariffs.

A scheme is outlined for ascertaining the true cost of supply, which claims to take into consideration such difficult factors as diversity, power factor, etc.

The type of metering equipment for obtaining the necessary measurements of the true cost of supply is discussed, together with the points to be considered in measuring maximum demand and power factor. Finally, a new type of kVAh meter is described and its performance, in practice, is given.

INTRODUCTION

Two of the most important considerations in the resale of bulk electrical energy are (*a*) economically sound tariffs and (*b*) accurate means of administering them. Furthermore, these considerations are yearly increasing in importance, owing to the increased quantity sold and the fact that the profit factor generally decreases as the load increases.

It would appear, from a superficial examination, that a scientific tariff should be applied, so that a consumer may be charged in accordance with the direct effect upon the bulk supply, automatic provision being made for diversity factor, power factor, and the like. Unfortunately, in most cases, such a tariff presents difficulties both in application and in measurement which prohibit its general use.

In practice, however, it is usual to approximate the accuracy of such a tariff by the use of empirical factors with a simple equation. Such a tariff may be economically sound when initiated, but it is possible that considerable errors may arise if the nature of the loads, both of the consumer and of the supply authority, vary to any large extent. It is suggested that the verification of these empirical factors, from time to time, is equally as important as the usual routine tests made upon the metering accuracy, and one of the objects of this paper is to suggest a method whereby these checks may be made.

It is realized that frequent changes to tariffs would meet with opposition, but it is felt that an accurate knowledge of the cost of a supply is essential when allocating tariffs for future consumers.

PRESENT-DAY TARIFFS EMBODYING EMPIRICAL FACTORS FOR LARGE SUPPLIES OF ELECTRICAL ENERGY

Usually modern tariffs are a combination of one or more of the following charges: (*a*) A kWh charge. (*b*) A kW maximum-demand charge. (*c*) A power-factor correction to the kW maximum-demand charge. (*d*) A fixed charge.

It is suggested that the variable factors used in such tariffs are empirical approximations only, for the following reasons:—

(1) The distribution costs and bulk-supply costs are generally combined, whereas it would be more accurate to separate them, since they are affected by the nature of the consumer's load in different ways.

(2) It is usual to regard the demand charge as a function of the consumer's load only, without any correlation to the bulk-supply demand. Actually, this diversity factor should be included in an accurate tariff.

(3) Most power-factor clauses ignore the relationship between the power factors at time of maximum demand, both of the consumer and of the bulk supply.

The importance of the errors, due to the above variable factors, depends upon the construction of the tariff, but it would appear that the values of these factors should be checked periodically. Hence it becomes necessary to check the true cost of the consumer's load to the supply authority. The method given, herein, to obtain this measurement, whilst not being devoid of errors, is, in the opinion of the authors, a practical solution to the problem without introducing serious complications.

A SUGGESTED METHOD OF OBTAINING THE ACCURATE COST OF CONSUMER'S LOAD TO THE SUPPLY AUTHORITY

In this scheme it is considered essential to divide all the items of cost of the supply to a consumer into two separate sections, distribution and production. This is necessary because the two sections are affected by the time of occurrence of the maximum demand in a different manner. For example, a consumer whose maximum demand occurs at the same time as that of the bulk supply, should be responsible for a greater portion of the bulk-supply maximum-demand charges than a consumer with an identical load except that his maximum demand occurs at some other time. On the other hand, both consumers should pay equal amounts towards the cost of distribution, since they load the distribution plant to an equal degree.

Considering the distribution costs first,

Let

P = kWh over period of supply under consideration;

p = Cost per kWh of distribution system;

X = Maximum demand of consumer in kVA;

a = Cost per kVA demand of distribution system;

and F_1 = Fixed charge per consumer for distribution system.

Then,

Consumer's share of total cost of distribution
$$= Pp + Xa + F_1$$

Reviewing this formula, one point which requires comment is the demand in kVA. It is suggested that this is preferable to a demand in kW, since the limit to the capacity of a distribution plant, consisting of cables, transformers, and switchgear, is the maximum permissible continuous current.

Referring to the production or bulk-supply costs, it is assumed that the supply authorities either purchase their supply in bulk, or, if they generate their own energy, that the cost can be allocated in a similar manner.

Let q = Cost per kWh of production cost;
Y = kW demand of consumer, at time of maximum kW demand of supply authority;
b = Cost per kW demand of production cost;
Z_1 = Power-factor correction to Y;
and F_2 = Fixed charge per consumer of generation or production cost.

Then the consumer's share of the total cost of production or bulk supply is given by

$$Pq + YbZ_1 + F_2$$

The total cost of the consumer's load to the supply authority is the sum of the consumer's share of distribution and production costs, given by

$$(Pq + YbZ_1 + F_2) + (Pp + Xa + F_1)$$
$$= P(q + p) + (F_1 + F_2) + (YbZ_1 + Xa) \quad . \quad (1)$$

These terms are all capable of measurement and interpretation, with the exception of the power-factor correction Z_1, for which the following method is suggested.

Computation of Power-Factor Correction Factor, Z_1

Fig. 1 is a diagram of the vectors of current and voltage at the time of bulk maximum kW demand of the supply authority. Assuming that the load is steady during the maximum-demand time-period, OA will represent kW, OC will represent kVAR, and OB will represent kVA. The bulk maximum-demand costs may be represented by TbZ_3, where T = kW maximum demand of bulk supply, and Z_3 = correction factor to T for power-factor charges. If the power factor is unity, then Z_3 must also be unity, but at other power factors Z_3 is generally greater than unity, depending upon the construction of the power-factor charge.

The additional cost of the bulk supply, represented by (OB–OA) × (charges per kW × constant) is due to the power factors of the loads of the consumers, and it is suggested that this extra cost should be allocated to the consumers in the ratio of the consumer's reactive demand at the time of bulk kW demand, to the bulk reactive demand at the time of bulk kW demand.

Furthermore, it is suggested that if the bulk demand has a lagging power factor, a consumer with a lagging load will cost more, whereas a consumer with a leading load will help to reduce some of the bulk demand charges

and hence should receive a rebate. The reverse would hold if the bulk supply were at leading power factor.

Therefore, the share of each consumer for the extra cost of bulk demand charges due to power factor will be

$$\frac{R_c}{R_b}(TbZ_3 - Tb)$$

where R_c = Reactive demand of consumer at time of bulk kW demand;
and R_b = Reactive demand of bulk supply at time of bulk kW demand.

From formula (1), the cost of the consumer's share of bulk-supply maximum-demand charges is given by

$$YbZ_1 = Yb + \frac{R_c}{R_b}(TbZ_3 - Tb)$$

Hence, by transposition,

$$Z_1 = 1 + \frac{R_c T(Z_3 - 1)}{R_b Y}$$

and

$$Z_1 = 1 + \frac{\tan \phi_c}{\tan \phi_b}(Z_3 - 1)$$

where $\cos (\text{arc} \tan \phi_c)$ = Power factor of consumer at time of bulk kW demand;
$\cos (\text{arc} \tan \phi_b)$ = Power factor of bulk supply at time of bulk kW demand.
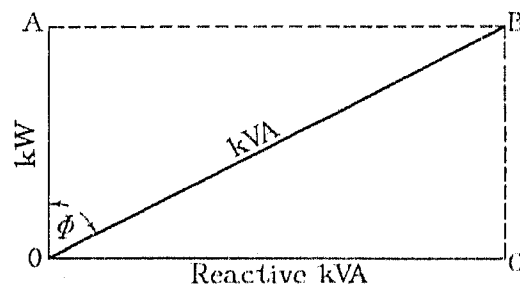
Fig. 1

If the bulk supply is operating on leading power factor, then the charge will take the form of the rebate:—

$$1 - \frac{\tan \phi_c}{\tan \phi_b}(Z_3 - 1)$$

Thus the total cost now becomes

$$P(p + q) + (F_1 + F_2) + Yb\left[1 \pm \frac{\tan \phi_c}{\tan \phi_b}(Z_3 - 1)\right] + X_a \quad (2)$$

Actual Charge made to Consumer

This charge is based on the measurements made by the metering equipment and the construction of the actual tariff, and can be expressed as follows:—

$$\text{Actual charge} = Pr + F_3 + VCZ_2 \quad . \quad . \quad (3)$$

where r = Charge per kWh made to consumer;
F_3 = Fixed charge (if any) made to consumer;
V = kW maximum demand indicated by the metering equipment;
C = Charge per kW made to consumer;
and Z_2 = Correction factor to V for power-factor charge.

A comparison of formulæ (2) and (3) will provide the profit factor, and this comparison may necessitate periodical changes to the empirical factors employed in the tariff. It is not suggested that, as a result of these surveys, immediate steps should be taken to adjust tariffs found to possess errors, since this might lead to controversy between the consumer and the supply authority. It is, however, suggested that the difficulties experienced by the sales department, in arranging tariffs with customers, might be reduced if accurate information were available concerning the magnitude of the existing tariff errors.

CHOICE OF AN EQUIPMENT FOR MEASURING LARGE ELECTRICAL SUPPLIES

The first essential of an equipment suitable either for measuring a simple tariff or for ascertaining the cost of consumer's load, is accuracy. It is proposed, therefore, to deal with the possible sources of error in detail when discussing the type of equipment necessary.

Measurement of Kilowatt-hours

Since the standard of accuracy of this measurement is high, and, furthermore, as it has been the subject of many recent papers, it is not proposed to pass any further comments upon it.

Measurement of Maximum Demand

The maximum-demand charge is necessary because of the limitations of the plant giving the supply, with regard both to the current-carrying capacity and to the period of time for which this capacity can be maintained.

There are two methods of measuring this maximum demand; the first makes use of thermal instruments, and the second is the "Merz block" system using integrating meters. In the case of the thermal instruments the time-interval over which the maximum demand is considered is decided by the expansion properties of the metal or liquid used in the apparatus, whereas in the case of the special integrating meter this time-interval is selected by some form of time-measuring instrument. It is not proposed to discuss any form of thermal indicator, since such instruments are not in general use for large supplies owing to their inherent errors. The "Merz block" system, however, is practically universal in its application, and the maximum demand is obtained by selecting the highest value of the integration of units over equal periods of time. These time-periods may fall in any one of the following classes:—

(a) Indefinite Time-Period.

Equal successive periods bearing no relation to the time of day.

(b) Definite Time-Period.

Equal successive periods commencing and finishing at specified times of day, a common period being the standard hour and half-hour.

(c) True Maximum-Demand Period.

Such periods are, in effect, indefinite time-periods, the period automatically starting at any time of the day and being simply dependent upon the load conditions.

An example will readily illustrate the significance of these three classes. Fig. 2 shows the load curves of two consumers A and B, and the sum of their loads represents the bulk supply. Each of the consumers has a maximum load of 1 500 kW, one occurring from 1 p.m. to 1.45 p.m. and the other from 1.15 p.m. to 2 p.m. The bulk-supply peak load will therefore be 3 000 kW over the period 1.15 p.m. to 1.45 p.m.

If the specified time-period be the half-hour, the following observations may be made:—

(1) If the maximum demands of A, B, and the bulk supply, are measured on the indefinite time-period system, the three demands cannot be accurately correlated, since they may vary between 2 250 kW and 3 000 kW for the bulk supply, and between 1 125 kW and 1 500 kW for A and B.

(2) If the maximum demand of the three is measured by the definite time-period system, say 1 p.m. to 1.30 p.m., etc., the values will be 2 250 kW for the bulk supply and 1 500 kW and 750 kW for A and B respectively during the period 1 p.m. to 1.30 p.m., and 750 kW and 1 500 kW
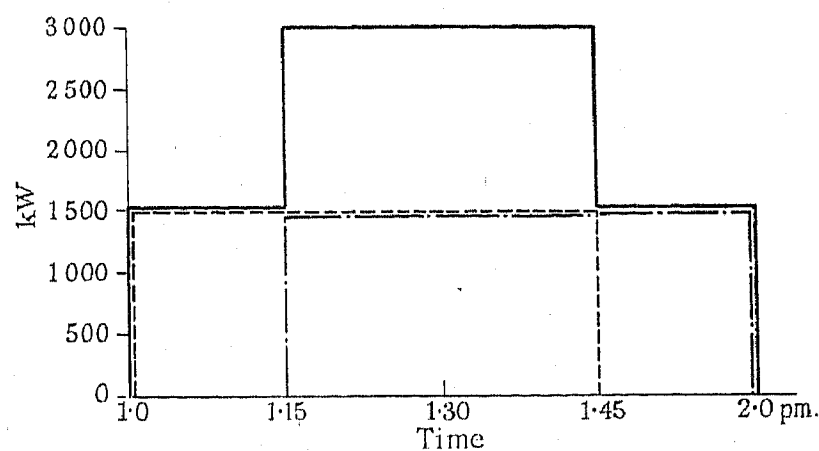
Fig. 2

- - - - - - - Consumer A.
—·—·—·— Consumer B.
——————— Sum of A and B (= bulk supply).

respectively during the period 1.30 p.m. to 2 p.m. These values are correlated since the sum of the consumer's maximum demands is equal to that of the bulk demand, but the values measured are not necessarily the highest demand over any half-hour.

(3) The highest demands occur between 1.15 p.m. and 1.45 p.m., when the values of A and B are 1 500 kW each, and the bulk demand is 3 000 kW. These values are the true demands.

Unfortunately, no apparatus is manufactured extensively which provides this true maximum demand, thus leaving two methods for general application. Of these two methods the definite time-period system is the more useful, owing to the comparisons which can be made if required. This system shortens the operation period by the reset time itself, but this inaccuracy can be reduced to a negligible magnitude by means of compensation or storage.

The particular time-period system which is to be adopted having been decided, there remains the choice of the apparatus to provide the required reading. Two types are available at present—recorders and indicators—and it is proposed to deal with each of these in detail.

Recorders

These may be grouped into two classes, the additive type and the resetting type. The former supplies a record of the units consumed; thus the demand has to be obtained by the interpolation of the load record and a time basis. The latter provides a record of the demand itself, the mechanism resetting to zero at the end of each period; hence a considerable amount of clerical work is saved by adopting this latter type.

Three different forms of recording maximum-demand mechanisms have been recently developed and manufactured in this country. The essential difference between these and the older types of recorders is the fact that the energy necessary to drive the recording mechanism is derived from a local supply, and not from the registering meter itself; hence, no undue load is imposed upon the meter, with a corresponding increase in accuracy at light load. Each of these mechanisms provides a printed record of the demand, period by period, together with the time of occurrence, by means either of figures or of graphs.* The inherent accuracy of these recorders, by virtue of their long scales, together with the time record, more than outweighs the larger cost of installation and maintenance, particularly in the case of large supplies, where the cost of the metering equipment is negligible compared with that of the plant installed.

Indicators

These mechanisms can be divided into two main classes: (a) " Held-on " type. (b) " Held-off " type.

The " held-on " mechanism is arranged so that the demand-pointer driving mechanism is located in gear by means of an electromagnet, and during the reset period this magnet is de-energized, with the resulting demeshing of the gears. In the " held-off " type, the reverse holds; the driving mechanism is held in gear by means of gravity, and is de-meshed during the reset period by the energizing of an electromagnet. Both methods are widely used, and each has its own particular advocates.

The " held-on " type suffers from the disadvantage of a constantly energized electromagnet, with the consequent electrical losses. More serious, however, is the wear which is liable to occur on the armature pivots, due to the alternating magnetic flux. This wear has been minimized on modern designs by the use of spring-supported bearings, but nevertheless it is a possible source of trouble.

The held-off type does not possess the above disadvantages, but, at the same time, it is liable to a serious degree of inaccuracy unless suitable precautions are observed in the timing circuit. If the supply should fail near the end of an operation period, and the time switch remain in operation, either because it is a hand-wound type or by virtue of a mechanical reserve in the case of the electrically-wound type, the held-off demand mechanism will not reset at the end of the period. If the supply should be resumed at the commencement of another operation period, the meter will start registering again, and a further reading will be added to the indication already given by this demand mechanism. Hence, the demand may register approximately twice the

* See J. HENDERSON: *Journal I.E.E.*, 1934, vol. 75, p. 185.

correct value. Such a condition is not possible with the held-on type, since immediately the supply fails, the demand mechanism will be automatically reset to zero, and the indication for that particular period will be lost. To obviate the possibility of this error arising with the held-off type, either a special form of time switch is used, operated by a clock which stops immediately the supply fails, or else precautions are taken to ensure that a constant supply is maintained for the demand mechanisms. When these precautions are observed the held-off type of indicator is to be preferred, accuracy being more easily maintained with the reduction of working strains.

The following points must be considered in either design, however, if accuracy is to be obtained: (1) Load imposed by the mechanism upon the meter. (2) Length of scale. (3) Freedom of movement between the demand and driving pointers. (4) Possibility of errors due to the resetting mechanism.

As regards (1), this does not lead to serious drawbacks in most modern indicators, since the load imposed by the mechanism does not as a rule produce an error larger than 1 per cent at $\frac{1}{20}$ full load; furthermore, since the meter is primarily intended to register a maximum demand, this error becomes small at the normal working range, which should be of the order of $\frac{1}{2}$ full load.

Difficulties due to (2) are unfortunately quite prevalent, and are aggravated in some cases by the supply authorities themselves. When equipments are installed, provision is generally made for future load, which often fails to materialize for a number of years, leaving the meter to work during the interim on an optimum load of the order of $\frac{1}{4}$ full load or even less. Such a condition not only increases the errors due to reading but at the same time increases the frictional errors mentioned above. It is suggested, therefore, that this point should be carefully watched when installing a new metering equipment, and, failing the possibility of changing the instrument transformers as the load increases, the authors advocate the use of instrument transformers with tapped windings.

To combat this error, the trend of modern design has been to increase the scale length. This, however, is counterbalanced by an increased load on the meter, so that a careful compromise has to be effected. Where extreme accuracy is essential, large-diameter scales are used, and, in many cases, this scale length is increased still further by the use of multi-turn mechanisms. In such cases, however, it is usual to remove the load from the meter, and supply the requisite driving torque from a separate mechanism, the meter itself operating some form of transmitter whereby impulses are sent to the demand driving mechanism.

As to (3), errors due to cohesion between the demand and driving pointers are practically non-existent in modern designs.

With regard to (4), inaccuracies due to the reset device are unfortunately fundamental in most gear changes, and are due to both backlash and the half-tooth error which is always possible when gears are meshed and de-meshed. The obvious remedy is to provide a large number of teeth on the two wheels used to effect the gear change. A further method which is sometimes used, removes the necessity for actually de-meshing any wheels, with a consequent reduction in this error.

Fig. 3 illustrates such a device, which embodies a differential. The drive from the meter is transmitted to one side of the differential, the other side being normally locked solid by means of an electromagnet. The centre bevel or planet wheel is coupled to the demand mechanism. During the reset period the locked portion is released, when a spring or weight allows the demand mechanism to reset to zero. If a suitably designed clutch is used for locking purposes, the errors due to this reset are considerably reduced when compared with the standard method of de-meshing the gears.

Providing due care is taken of these points, the modern indicator can be guaranteed to be accurate within 0·5 per cent of the full-scale reading, and, in the case of large multi-turn dials, within 0·1 per cent of full scale.

To complete the maximum-demand equipment, a time switch is necessary to provide the requisite periods for operation and reset. If commercial accuracy is desired, hand-wound or electrically-wound time switches with or without mechanical reserve are generally used. When, however, held-off demand mechanisms are used, it is

In conclusion it is suggested that whilst demand cannot be registered so accurately as units, the measurement can be made with reasonable precision if the various points mentioned are carefully investigated.

Measurement of Power Factor

The following three distinct measurements are required to provide the necessary corrections for power factor and also to give corrections for an accurate check of the cost of the supply: (a) The maximum demand of the consumer in kVA. (b) The average power factor of the consumer's load, taken over the same period as the bulk kW maximum demand. (c) The average power factor of the consumer's load at the time of his kW maximum demand. (This measurement will not be required if the consumer is charged on a kVA basis.) These readings may be obtained either by means of reactive-kVA meters or by kVA meters, both being equipped with maximum-demand indicators and recorders, whose time-periods are synchronized with the kW demand mechanisms.

Drive to maximum-demand driving mechanism

Brake operated by resetting electromagnet

Differential

Drive from meter
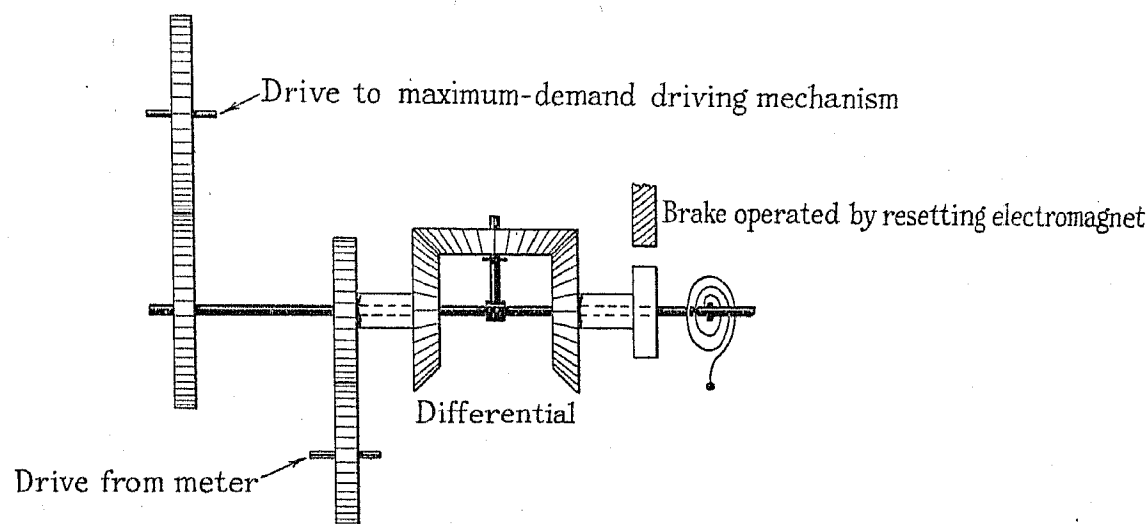
Fig. 3

usual to provide a time switch without reserve, i.e. one which will stop immediately a cessation of the supply occurs. If precision accuracy is required, some form of high-grade clock, generally of the electrically-wound type, fitted with a suitable contacting device, is used to supply the requisite timing intervals.

As has already been stated, the definite-period method necessitates some form of compensation or storage device when extreme accuracy is necessary. The compensation method is generally adopted in the case of indicator mechanisms, and consists of arranging the gearing so that the demand-pointer drive travels at a slightly faster rate than the meter rotor; in the ratio of the true demand period to the actual demand period. Such a method relies for its accuracy upon the assumption that the load, throughout the reset, is similar to that during the operation period itself, and since the reset period is only a few seconds, inaccuracies due to this assumption are extremely small. The storage method is generally adopted on recorder mechanisms; it consists of some form of spring device whereby units received during the reset period are stored and passed to the printer mechanism in the next period. Here again the errors introduced by this displacement of units are extremely small.

The term "average power factor" may lead to some controversy, since the following two values of average power factor can be obtained, depending upon the method of measurement:—

(1) Average power factor (vectorial value)

$$= \frac{\text{kW max. demand}}{\sqrt{\left[(\text{kW max. demand})^2 + \left(\frac{\text{kVAR demand at}}{\text{time of kW demand}}\right)^2\right]}}$$

This value is obtained by the use of kW and kVAR demand meters.

(2) Average power factor (arithmetical value)

$$= \frac{\text{kW maximum demand}}{\text{kVA demand at time of kW max. demand}}$$

This value is obtained by using kW and kVA demand meters.

It is obvious that these two values will be the same when the power factor is constant throughout the period under consideration, but any variations in power factor will always cause the arithmetical value to be lower than the vectorial value. Fig. 12 shows the maximum

errors which can occur between these two values with power factors varying between unity and zero lagging, and, whilst it is not suggested that these particular errors will occur in practice, it will be seen that the errors arising under practical conditions can be of sufficient magnitude to cause controversy unless the point is especially watched.

Considering the measurements actually required, it would appear that the arithmetical value of average power factor should be used for the measurements of items (a) and (c) whilst the vectorial value would be the correct one to use for (b), providing the bulk supply was measured under identical conditions. The apparatus required to obtain these measurements, namely the reactive-kVA demand meter and the kVA demand meter, will now be discussed in detail.

Measurement of Reactive-kVA Demand

One of the chief disadvantages of all reactive-kVA demand meters is that the direction of rotation reverses if the power factor changes from lagging to leading. The usual methods of overcoming this difficulty are: (1) The fitting of ratchet and pawls to prevent reverse rotation. (2) The installation of a potential change-over relay, which reverses the potential supply in the event of a change of power factor. These methods are effective and comparatively simple to use, and it is essential that they should not be overlooked when such an equipment is installed.

Measurement of kVA Demand

Classification of Existing Types.

There appears to be no single instrument on the market which will register the product of a.c. volts and a.c. amperes; fortunately, however, there are many ingenious instruments available which approximate this product within varying degrees of accuracy, dependent upon the variation of the circuit conditions. Generally speaking, these instruments can be subdivided into three main classes: (a) Compensated kWh meters. (b) Ferraris-motor meters. (c) Mechanical summation meters.

Class (a) utilizes a standard kWh meter, compensated in some manner whereby it will register kVAh within certain limits of accuracy over a specified range of power factor. For example, a standard kWh meter will register 28 per cent slow if it is scaled in kVAh when operating on a system whose power factor is 0·72 lagging. If, however, the voltage flux is arranged to lag 22° more than the usual 90° (see Fig. 4), the theoretical errors of such a meter will be 7·28 per cent when the meter is registering over a power-factor range of unity to 0·72 lagging. These errors can be reduced still further by averaging them, when the final theoretical errors of the meter will become ± 3·64 per cent. Such errors are, of course, too large to permit of this type of instrument being used on large supplies, particularly when the range of power factor is large. Further improvements have recently been made to this type of meter, whereby a number of voltages, displaced at predetermined phase angles, are applied to the voltage coils for varying periods of time. These periods are automatically arranged so that the meter substantially registers kVAh.

Class (b) uses an instrument whose accuracy is independent of the power-factor range, but unfortunately the instrument is accurate only over a comparatively small range of voltage. Furthermore, the instrument loses accuracy if the load becomes unsteady. If a constant voltage could be maintained upon the system, an ammeter scaled in kVA would present a satisfactory solution to this measurement. The Ferraris-motor type is, in fact, such an ammeter, the motor replacing the ammeter movement and rotating as a function of the time and the square of the current. Compensation for voltage fluctuation is obtained by an ingenious form of magnetic shunt controlled by a voltage winding. The fact that the speed of rotation is not a linear function of the current presents the most serious disadvantage to this method of registration.

Class (c), which has the disadvantage of high cost, is at present made in two distinct types. The first type uses
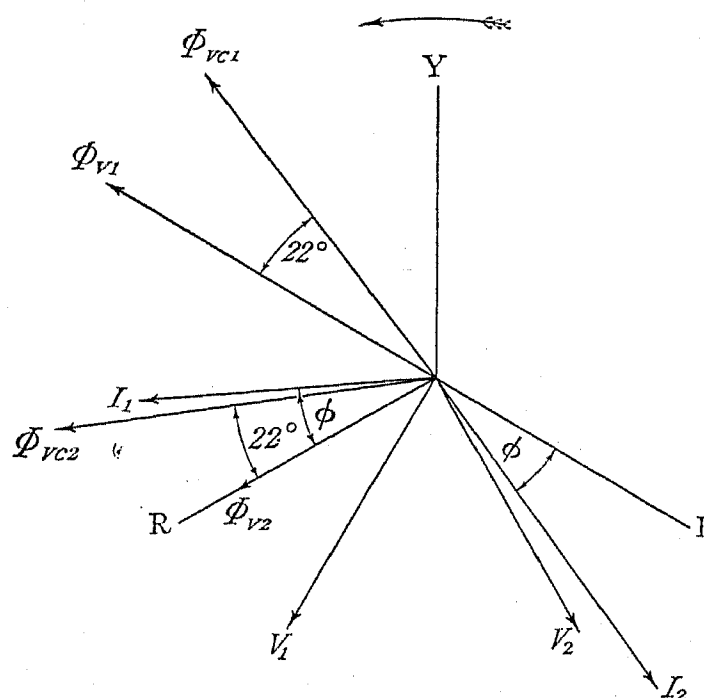
Fig. 4

two elements, one measuring kWh and the other kVARh. The drives from these two elements are connected through five separate gear-trains to a common registering mechanism, this mechanism being made to operate from the drive with the greatest speed of rotation. These gear trains are of a differential form and, in effect, produce a compensated type of kWh meter for five separate ranges of power factor; hence the accuracy and range of such a meter are very much larger than those of Class (a). This first type of Class (c) meter operates with a theoretical error of ± 0·5 per cent for a power-factor variation from unity down to zero lagging. Should the meter be required to operate on leading power factor, this can be accomplished by installing a potential change-over relay.

The second type of Class (c) meter uses two elements, measuring kVARh and kWh respectively, coupled through a special drive to a common register. Fig. 5 illustrates schematically the arrangement of this special drive, which incorporates a ball riding on two discs. It is obvious, from an examination of this figure, that the speed of K is proportional to the speed (v_C) of C, and $v_C = \sqrt{(A^2 + B^2)}$, A being proportional to the speed of

K

— Kilovolt-ampere-hours

C

B   A

90°

To kilovar-hr.meter   To kilowatt-hr.meter

Fig. 5

B Y R

Y

R

S

Tapped
reactors or
resistances

B

Potential
Transformer

Current
transformers

M

KILOVOLTAMPERE. HRS.

Ferraris
motor

F

Contacts

kVA meter

Relay   P
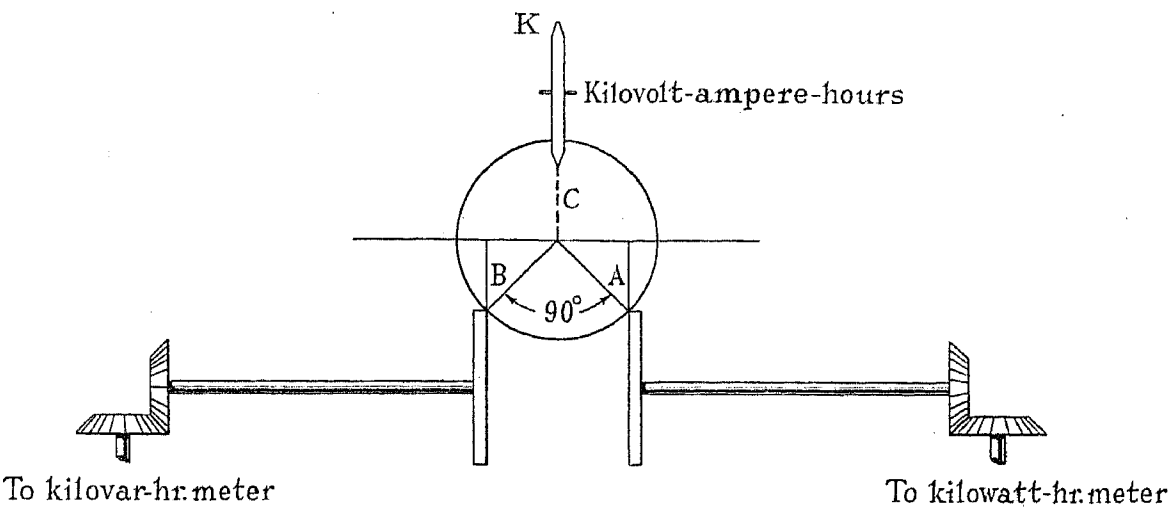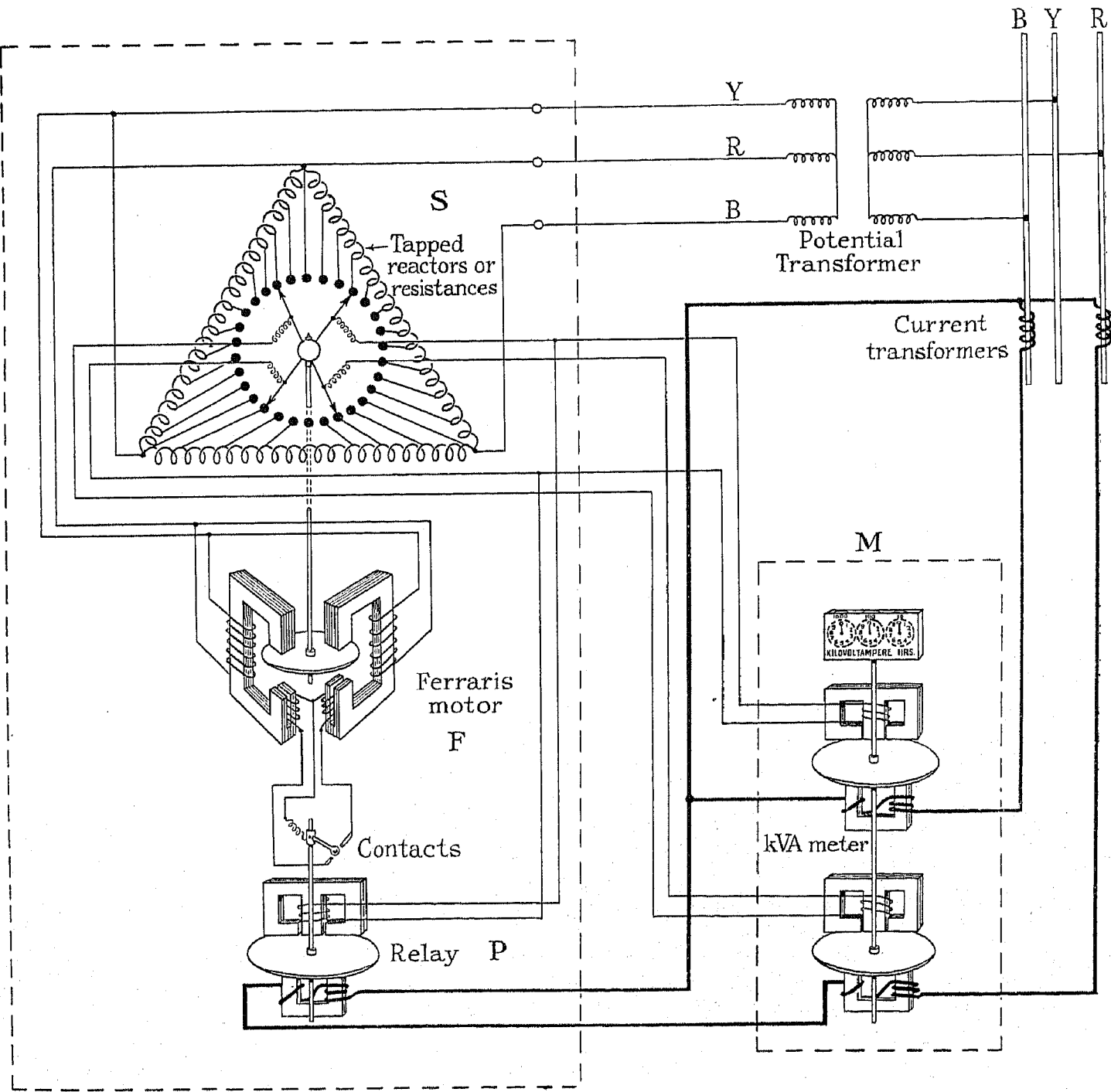
Fig. 6

the kWh meter and B being proportional to the speed of the kVARh meter.

Both these types measure the arithmetic value of kVA or kVAh, since the computation of the kVA is made from the two values kW and kVARh instantaneously and not at the end of the time-period of maximum demand.

A further method, not classified above, has been recently introduced. It uses dynamometer or moving-coil instruments in conjunction with rectifiers, chiefly of the dry metal type. The main disadvantage of such a system, apart from the errors introduced by harmonics, appears to be the initial cost, particularly in the case of polyphase equipments, where a comparatively large number of rectifiers would be required.

A New Type of kVA Meter.

An ideal method of making a kVA or kVAh meter would be to use an induction-type watt-hour meter and arrange for the voltage and current to occupy the same relative phase relationship independent of the power factor of the system. A meter based on this principle has recently been developed by the authors. Whilst the method is not new, the apparatus has several novel features which are worthy of a brief description.

The actual apparatus consists of two separate items; the first is a standard kWh meter fitted with demand indicator and, if necessary, means of transmitting impulses to a recorder; and the second, a power-factor compensator, a piece of apparatus which provides voltages whose phase displacements follow that of the current vectors. This apparatus consists fundamentally of three separate items—a power-factor relay, a phase-shifting device, and a motor for driving the phase-shifting device. Fig. 6 illustrates the complete equipment, M representing the meter which is to register kVAh and kVA demand, P the power-factor relay, S the phase-shifting device, and F the driving motor.

The power-factor relay simply consists of a motor element, accurately calibrated for power factor, the rotor system being coupled to a contact which can make circuit with either of two fixed contacts mounted one on either side of it. The phase-shifting device consists of three delta-connected resistances or chokes, suitably arranged with taps which are connected to a circular switch containing 36 contact studs, these studs being traversed by two pairs of brushes rigidly fixed at 60° apart. The taps are arranged so that voltages of equal magnitude, but displaced by 10° vectorially one from the other, can be obtained through the whole of the 360°. The values of the taps are determined as shown below.

BA, AC, and CB (Fig. 7) represent the three voltages of a 3-phase system; AD represents one of the voltages selected from the delta, and EF a second voltage, equal in magnitude to AD but displaced by 10°. It is obvious that BE = $K \sin 80°$, where K is a constant, and AD = $(\sqrt{3}/2)$AB. Thus, if AB represents 100 ohms, the tappings are arranged as shown in Fig. 7.

It is necessary to arrange for the voltage-selector brushes to bridge across the contacts, so that the voltage supply to the meter M and relay P is never discontinued. It follows that a certain error will arise due to the short-circuiting of the contacts, which in effect removes some of the resistance from the delta. This error, however, is

reduced to a minimum by reducing the time of bridging the contacts to a small quantity. This is achieved by converting the continuous rotation of the driving motor into a series of intermittent drives by the introduction of a Geneva escapement.

If it were possible to make the variation of the voltage phase-displacement infinitely variable, such a meter would give an accurate registration of kVAh or kVA demand. Unfortunately such a design cannot be realized in practice, and hence a compromise has been effected by allowing the voltages to be displaced 10° apart, when the theoretical error of the meter becomes 0·4 per cent, which is negligible for all practical measurements.

The advantages of such a method are: (1) Comparative simplicity, relative to most of the existing methods. (2) Inherent accuracy, which is maintained through the whole 360°, without the necessity of an extraneous relay. (3) The provision of the compensator as a separate item
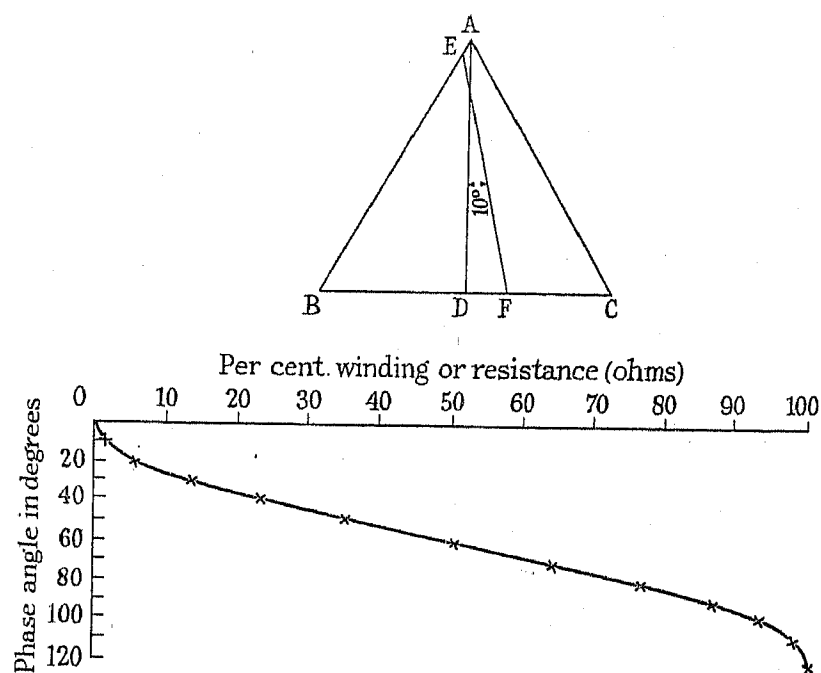
Fig. 7

reduces the calibration difficulties attendant upon most kVAh meters, the meter portion being calibrated as a standard kWh meter and the compensator being simply subjected to a standard routine test.

The motor in the equipment may be of either the Ferraris or the synchronous type, or may even be a ratchet device with 2-way rotation. In the case of the Ferraris type of motor the field coil is constantly energized, and rotation is produced by short-circuiting one of the two shading coils fitted on the magnet. By this method, excessive wear due to sparking is eliminated at the contacts of the power-factor relay, since the voltages on the shading coils are small.

In operation, the movable contact of the relay floats until a phase displacement takes place between the voltage and current energizing this relay. When this phase displacement occurs, the moving contact closes circuit with one of the two fixed contacts, which short-circuits one of the shading coils, and the Ferraris motor commences to rotate, driving the two pairs of brushes around the voltage-selector contacts through a special form of gearing. As the brushes rotate, voltages of different phase displacement are selected and impressed
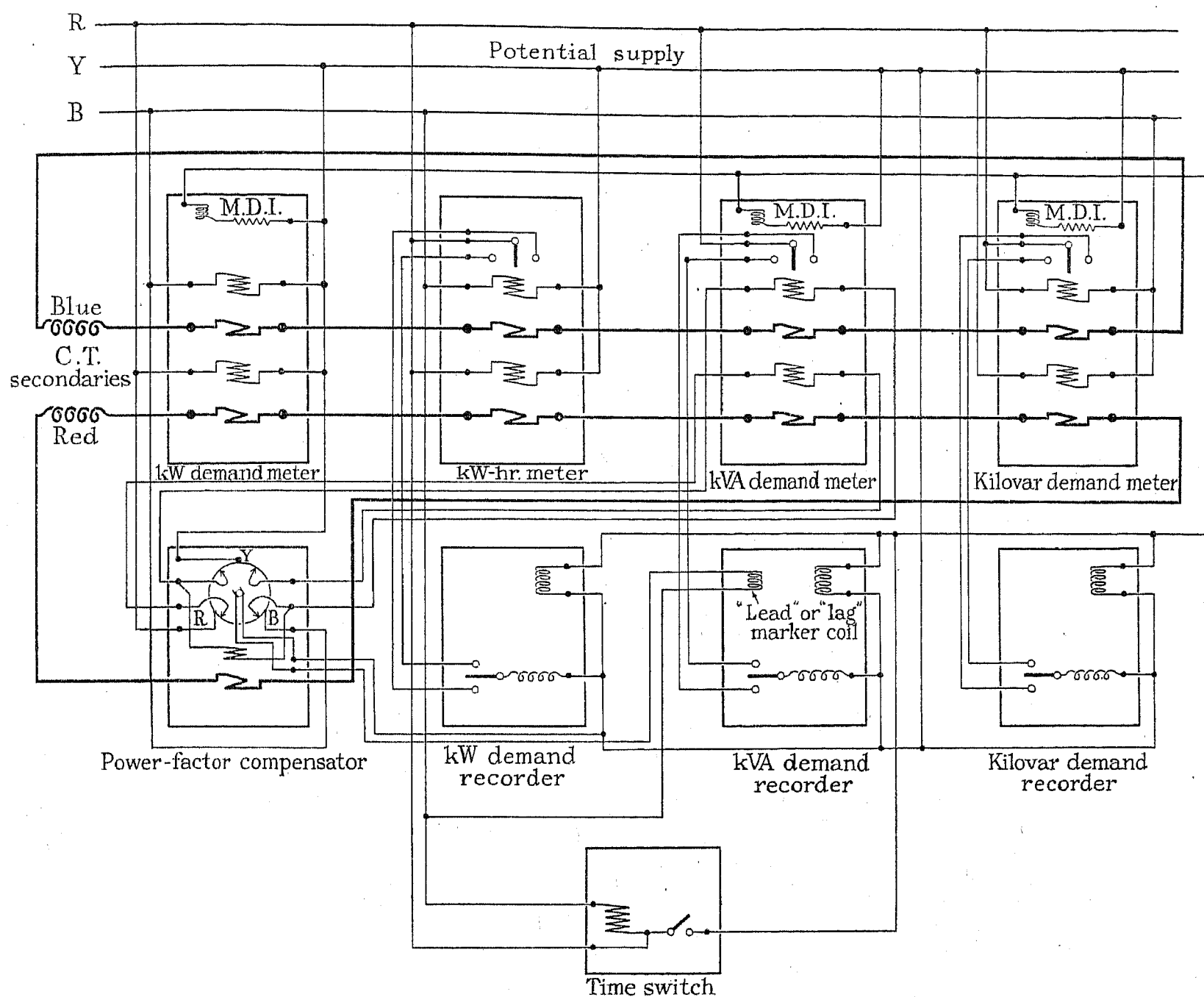
Fig. 8—Complete metering equipment.
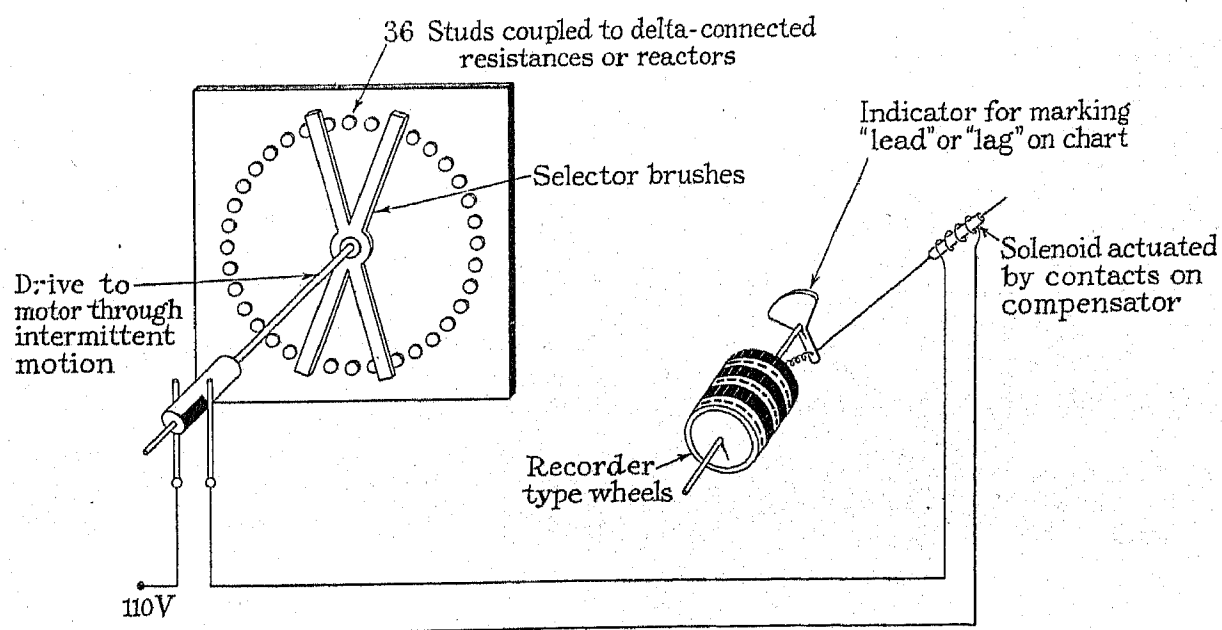
Fig. 9—Device on kVA meter for recording leading or lagging power factors.

upon both the power-factor relay P and the meter M, until such time as the voltage is in phase with the current of the supply, when the relay P loses its torque, and the shading coil of the motor is open-circuited. Hence the voltage impressed upon the meter M will keep the same phase relationship with the current of the supply, and thus the meter will register kVAh. Should the power factor of the supply vary again, the same procedure will occur until a new voltage is obtained.

The Complete Metering Equipment

The various measurements having been discussed in detail, it only remains to specify the equipment as a whole. The measurements required to give complete information for ascertaining the true cost are as follows:—

Consumer's Load.

(a) The kWh. (b) The kW demand at time of the kW demand of the bulk supply. (c) The power factor of the load at the time of the kW demand of the bulk supply. (d) The kVA maximum demand.

Bulk-supply Load.

(e) The time of occurrence of the maximum kW demand. (f) The power factor of the load at maximum kW demand.

The bulk-supply load measurements will have to be obtained from the supply authority, and the measurements of the consumer's load can be obtained from a metering equipment such as is shown in Fig. 8, comprising: (1) kW demand indicator meter. (2) kWh meter with kW demand recorder. (3) kVA demand indicator meter together with kVA demand recorder complete with power-factor indication. (4) kVAR meter with kVAR demand recorder. The whole of the demand mechanisms will be operated from a single time-switch on the definite-period system and synchronized with the bulk-supply timing arrangements.

It will be noted that the kVA demand recorder is fitted with power-factor indication; this is only necessary when there is the possibility of the load power-factor changing from lagging to leading and vice versa. In practice, this indication is given by a simple device as illustrated in Fig. 9. The voltage selector switch on the power-factor compensator is, in effect, a power-factor indicator; hence contacts fitted on the shaft (unlike most power-factor indicators there is plenty of torque on this mechanism) can be made to energize an auxiliary coil on the recorder to indicate on the chart when the power factor is leading.

The apparatus shown in Fig. 8 could be readily mounted in a small portable cubicle, enabling the supply authority to obtain a check of the accuracy of the existing tariff and at the same time to check the accuracy of the existing metering equipment.

In conclusion, the authors wish to extend their thanks to their colleagues for help received during the preparation of the paper, and also to the Central Electricity Board and Messrs. Metropolitan-Vickers Electrical Co., Ltd., for kindly permitting it to be published.

Table

Consumer	Supply cost									Distribution cost*							Total
	Consumer's kW at time of bulk kVA	Correction factor	Corrected kW	Cost per kVA of bulk supply £	Supply maximum-demand cost £	Units consumed	Cost per unit of bulk supply pence	Supply units cost £	Total supply cost £	Consumer's max. kVA	Distribution cost per kVA £	Distribution max.-demand cost £	Units consumed	Distribution cost per unit pence	Distribution units cost £	Total distribution cost £	Cost of supply and distribution £
A	1 000	1·795	1 795	2·31	4 160	3×10^6	0·15	1 875	6 035	1 800	1·5	2 700	$3·0 \times 10^6$	0·1	1 250	3 950	9 985
B	1 000	1·000	1 000	2·31	2 310	3×10^6	0·15	1 875	4 185	1 000	1·5	1 500	$3·0 \times 10^6$	0·1	1 250	2 750	6 935
C	1 000	3·930	3 930	2·31	9 085	3×10^6	0·15	1 875	10 960	5 600	1·5	8 400	$3·0 \times 10^6$	0·1	1 250	9 650	20 610
D	1 000	0·08 rebate	80	2·3	185 rebate	3×10^6	0·15	1 875	1 690	2 250	1·5	3 370	$3·0 \times 10^6$	0·1	1 250	3 620	5 310
E	1 000	2·352	2 352	2·3	5 450	3×10^6	0·15	1 875	7 325	2 720	1·5	4 080	$3·0 \times 10^6$	0·1	1 250	5 330	12 655
F	—	—	—	—	—	3×10^6	0·15	1 875	1 875	5 600	1·5	8 400	$3·0 \times 10^6$	0·1	1 250	9 650	11 525
Bulk†	9 020 kVA × 2·31 £ per kVA				20 820	18×10^6	0·15	11 250	32 070	—	—	—	—	—	—	34 950	67 020

* Distribution tariff = £1·5 per kVA + 0·1d. per unit.

† Bulk-supply purchase tariff = £2·31 per kVA + 0·15d. per unit.

APPENDIX 1

In order to illustrate the authors' method of obtaining the cost of a consumer's load to the supply authority, a hypothetical case will be worked out of a supply authority whose total load is taken by 6 consumers. Each of these consumers is assumed to take 3×10^6 units per annum with a maximum demand of 1 000 kW. Five of the consumers have a maximum demand which occurs at the time of bulk kVA demand, while the sixth has no load at this time. The power factors of the various loads at the time of bulk kVA demand are shown in Fig. 10, and the complete analysis is given in the Table on page 690.

It is observed from the Table that the load of Consumer C, with the worst power factor, costs 3 times that of Consumer B, with unity power factor. Consumer D, with the leading power factor, costs least of all owing to
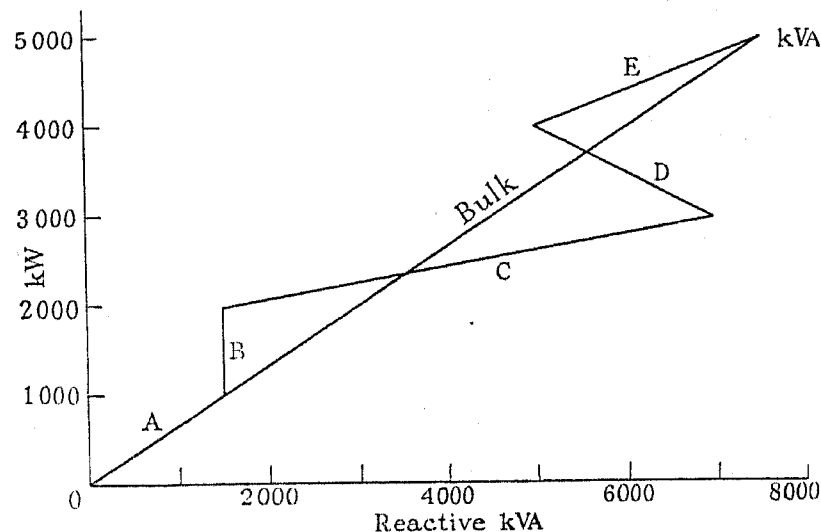
Consumer	kW	Reactive kVA	kVA	ϕ	Cos ϕ
A	1 000	1 500	1 800	56° 19′	0·555
B	1 000	0	1 000	0°	1·000
C	1 000	5 500	5 600	79° 40′	0·179
D	1 000	2 000 (lead)	2 250	63° 35′	0·445 (lead)
E	1 000	2 500	2 720	68° 24′	0·372
Bulk	5 000	7 500	9 020	56° 19′	0·564

Fig. 10

the nature of his load, but this consumer has a higher distribution maximum-demand cost than Consumer B.

Consumer F, whose power factor is the same as that of Consumer C, is not allocated any bulk-supply maximum-demand costs, but, owing to the high value of the kVA, the distribution maximum-demand charges are high and the total cost is comparable with that of Consumer E.

APPENDIX 2

Difference Between Values of Average Power Factor Obtained by Vectorial and Arithmetical Methods

Fig. 11 represents the load of a consumer whose power factor changes during the maximum-demand period between unity and zero lagging. We have

Average power factor (vectorial method) $= \cos \phi$
Average power factor (arithmetic method)

$$= \frac{OD + DE}{(OD/\cos \alpha) + (DE/\cos \beta)}$$
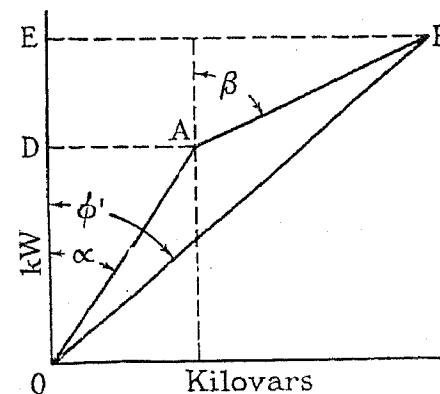
Fig. 11
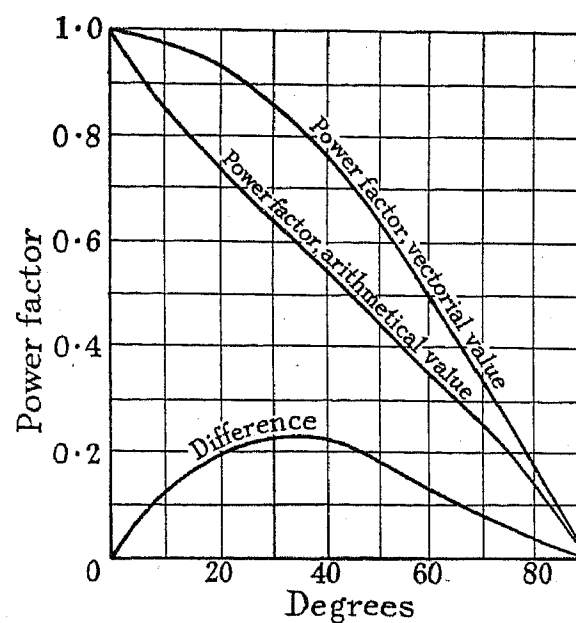
Fig. 12
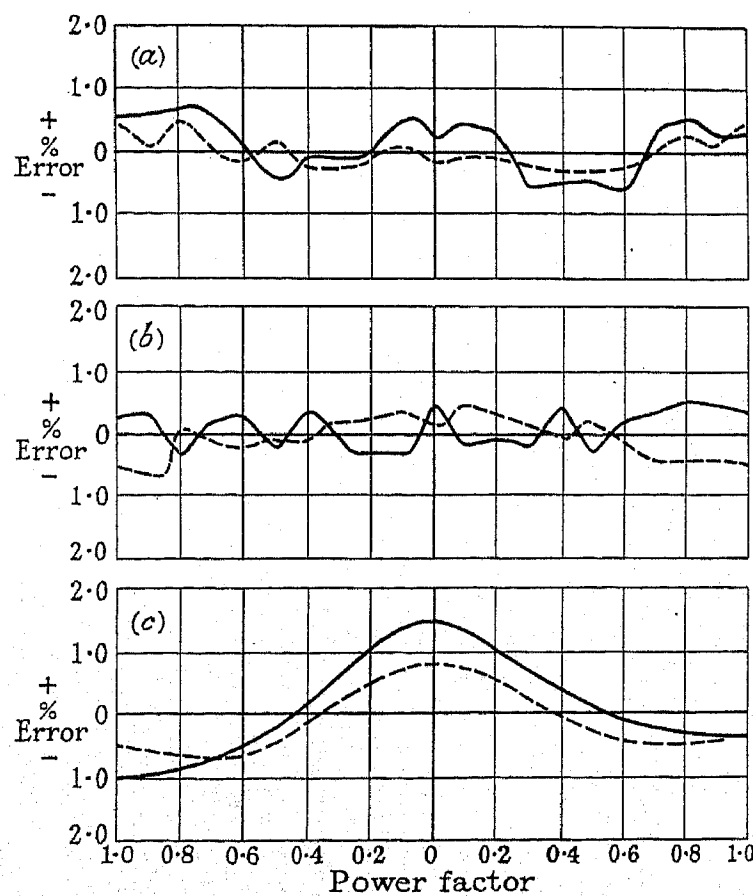
Fig. 13

(a) kVA meter at full load.
(b) kVA meter at $\frac{1}{20}$ full load.
(c) kVA meter at full load, with unbalanced voltages: R–B, 117 volts; R–Y 114 volts; B–Y, 102 volts.

———— Lagging power factor.
- - - - - Leading power factor.

The greatest difference between these two values must occur when $\beta - a = 90°$. Under these conditions Fig. 12 shows the magnitude of the differences for various power factors. Whilst differences of this order are not likely to be obtained in practice, it will be realized that due care must be taken to select the correct measurement.

APPENDIX 3

The curves reproduced in Fig. 13 illustrate the results which have been obtained with a meter similar to that described in the paper. Fig. 13(a) gives the errors obtained with the meter running at full load, for varying power factors, whilst Fig. 13(b) gives the errors over the same range of power factor with the meter running at $\frac{1}{20}$ full-load speed. It will be seen that the errors are within ± 0.75 per cent.

A similar test was made at full-load speed with the primary voltages unbalanced. It will be realized that the accuracy must be impaired by such a condition. This applies to all meters using a form of reactivator for obtaining kVARh measurement. The results [Fig. 13(c)], even under such severe conditions, are of interest since they are within a $2\frac{1}{2}$ per cent range.

When the power factor of the system changes, a certain time must elapse during which the compensator is selecting the new voltage vector; at this period the meter is not measuring true kVAh. The curves in Fig. 13 demonstrate that this error is not large, since they were taken

with the compensator still in operation. It was felt, however, that the time of instability might prove of interest. Fig. 14 shows these times of instability for different displacements of the phase angle, with the
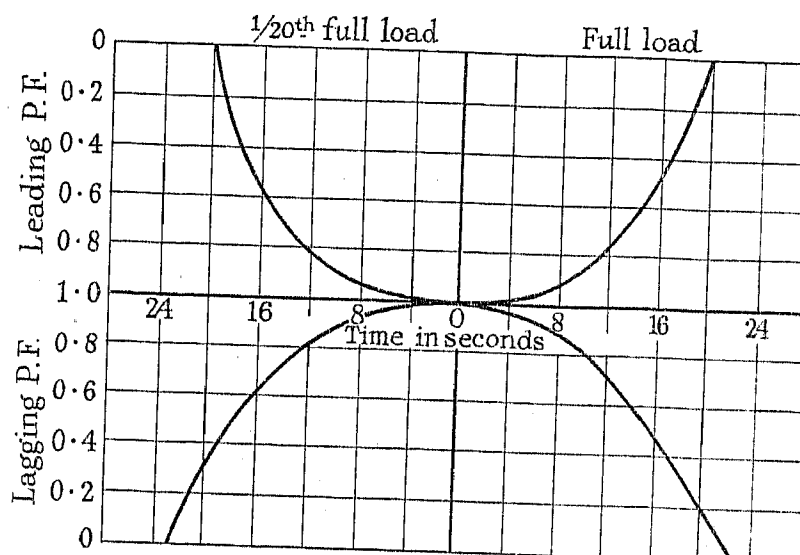
Fig. 14.—Times of instability for different displacements of phase angle.

meter running at full load and at $\frac{1}{20}$ full load respectively. In each case the change of power factor was from unity. These figures indicate that there is little error to fear from this period, since the time of change will be small for most power-factor changes which will be encountered in practice.

DISCUSSION BEFORE THE METER AND INSTRUMENT SECTION, 6TH DECEMBER, 1935

Mr. E. W. Hill: I should be glad if the authors would explain with a little more detail the derivation and the physical implications of equation (2), especially the trigonometrical part of the expression within the square brackets.

An interesting point arises about the time-periods of maximum-demand indicators. Should there be a periodic recurrent characteristic in the load curve the maximum-demand period may miss the peak-load time day after day if we use the Merz block system of time-periods definitely related to the time of day. I should like to recall the fact that the pendulum-type clock meter, fitted with a self-tripping maximum-demand indicator, has a tripping time-period which is indefinite in the sense of being unrelated to the time of day; furthermore, the time-period is not necessarily an exact half-hour (assuming this to be the nominal period), but the scale of the demand indicator is graduated to compensate for this. It results, however, that the time-period after some days ranges over the whole set of possible periods in relation to the time of day, with a good chance of coinciding at some time or other with the time of the peak value of the load.

I think the authors under-estimate the range of voltage covered by the Ferraris-motor type of kVA maximum-demand indicator, as this is at least $12\frac{1}{2}$ per cent above and $12\frac{1}{4}$ per cent below the normal value, which is amply sufficient in practically all circumstances. Their statement that an ammeter scaled in kVA would present a satisfactory solution to kVA measurement is one, I think, that cannot easily be substantiated in view of the

fact that instantaneous values of the demand are of no practical use for maximum-demand measurement.

I am glad to see that the authors lay considerable emphasis upon the differences between the arithmetical-sum and the vectorial-sum method of estimating the average power factor. I discussed this point in considerable detail in a paper[*] which I read before this Section in 1929, and now I only feel it desirable to point out that the discrimination between arithmetical and vectorial sum applies in addition to the convention used for defining polyphase kVA.

When dealing with the use of rectifiers and d.c. instruments for the purpose of measuring kVAh, the authors overlook a very important difficulty, namely that of obtaining a smooth d.c. wave from the rectifiers. If this is not done properly the ripples in the rectified current can associate themselves with those in the rectified voltage in such a way as to produce many of the phenomena of alternating current and voltage phase relationships.

The delta-connected resistance network mentioned on page 688 calls for some comment. The calculation of the resistance values is in effect an interesting geometrical problem of finding a line of constant length which shall turn itself inside a given triangle by successive stages into such angles as are required. The authors have compressed their argument so much that they give merely a bare clue as to how the calculation is effected; it would, I believe, be of use to others if this particular point were dealt with a little more fully.

I have to call attention to the obvious point that as the

[*] *Journal I.E.E.*, 1929, vol. 67, p. 1228.

power-factor relay has its series coil in one phase only, the meter must be subject to impairment of its accuracy if the 3-phase loading is unbalanced. The authors have explained, however, that a polyphase form of the power-factor relay would remove this objection. They have also disarmed me in a further criticism I might have made, to the effect that such an equipment is rather expensive and not well adapted to small installations, by saying that it is not proposed to use this necessarily for tariff measurements but for the purpose of obtaining information.

Mr. R. S. J. Spilsbury: I notice that the authors give the accuracy of a modern single-turn maximum-demand indicator as within 0·5 per cent. I presume this refers to a large-diameter scale: the type frequently met with, having a scale of about $2\frac{1}{2}$ in. diameter, can have errors of the order of 1·5 per cent, even at full scale. Considerable variations are also met with in indicators operated by impulses, owing to the possibility of an impulse being just missed when the indicator trips. If a given load is held constant for a sufficient time a definite reading is obtained, but a test over a single period may give an indication fully 1 per cent different from this value.

Turning to the authors' new kVAh meter, the most interesting point seems to be the use of the delta-connected network as a form of phase-shifter. My recollection is that a meter was invented many years ago which was substantially identical in principle with the authors' device, but which employed a phase-shifting transformer of the usual type. It would be interesting to know whether this meter operated satisfactorily, or whether it was merely a theoretical conception. The delta network is certainly a very simple device, and the fineness of subdivision provided is sufficient for the purpose.

With regard to the spacing of the tappings, the argument near the bottom of col. 1, page 688, is so condensed that it is not very helpful, while the method of plotting the curve of Fig. 7 also rather tends to obscure the matter. It is actually easy to show that the tappings along a side of the delta should be symmetrical about a median line such as AD in Fig. 7; and that the resistance x of any section such as DF, expressed as a percentage of BC, is given by $x = 100 \sin (10n + 30) - 50$, where n is the number of steps required to reach F from D.

The authors claim that the meter portion can be calibrated as a standard kWh meter. While this is no doubt true in the sense in which they intend it, the meter will have to be to some extent a special type, because the voltage applied to it is not the line voltage but $\sqrt{3}/2$ times this value.

With regard to the errors caused by unbalance, any general statement seems impossible, since the effect of the negative-sequence quantities will be different for each position of the power-factor compensator. In reactive-kVAh meters employing cross-phasing of similar type the errors are fortunately much smaller than might be expected, and from the authors' results given in Fig. 13 this appears to be the case for the kVAh meter also.

While I appreciate that the description of the kVAh

meter is only incidental to the main purpose of the paper, I think some further details of the construction would be of interest. For example, an indication of the steps which have no doubt been taken to make the power-factor relay sensitive to low currents while avoiding undue hunting at high currents would be useful, as would a description of the special gearing used to drive the power-factor compensator.

Mr. F. Byrne: In the first part of the authors' remarks there is the underlying assumption that electricity supply tariffs will be fixed on a kVA and not a kW basis. During recent years, however, there has been a marked trend to show that commercial adjustments for penalizing consumers on a power-factor basis are becoming of diminishing importance. A number of reasons for this may be given, including the rapid increase in the domestic load, of favourable characteristics, and, not the least effective, the stimulus given by the national electricity supply tariffs, which disregard the power factor entirely down to values of 0·85.

Tariffs on a kVA basis inevitably encourage consumers to install power-factor correctors, with the danger of producing leading power factor at certain times. The authors suggest that such consumers should receive a rebate, but I would submit that the considerations which apply to a consumer taking a supply at a lagging power factor apply equally to a consumer whose supply power factor is leading. If anything, the latter should be discouraged, not encouraged, because of the operating difficulties which his supply would introduce, namely, bad voltage regulation and instability of synchronous machinery.

The authors' kVA recorder is not a new device, and there does not seem to be very much in the analysis of supply tariffs which could not be dealt with satisfactorily by the existing methods of measurements.

Dealing with the technical features of the kVA meter described by the authors, it possesses one drawback which is common to all devices employing the cross-phase system of obtaining voltage displacements. The instrument may be correct when the load is symmetrical, and under unsymmetrical load conditions it would, in fact, respond to the negative phase-sequence component, but it would respond, unfortunately, in the opposite direction; that is, it would respond positively to a negative phase-sequence component. The authors have not failed to notice this point, as the following statement in Appendix 3 shows: "It will be realized that the accuracy must be impaired by such a condition." I am rather surprised that they have managed to get the device so accurate under the unsymmetrical conditions mentioned, and I should like to have their assurance that the testing method they applied was free from the same defect. They have chosen an unsymmetrical voltage, but I should like to know what would be the accuracy of their method if the currents were unsymmetrical to the same extent. This, of course, is the condition which is more likely to be encountered in practice.

Mr. H. S. Petch: It seems to me that the authors, in their desire to avoid a discussion on tariffs, have condensed the first part of their paper to such a point that their argument is difficult to follow.

Will they please state what is the volt-ampere con-

sumption of the delta-connected network of resistances in the kVA instrument?

Mr. A. J. Pitt: I am most interested in the relation between the maximum kVA demand and the time of day. Although we are trying to achieve uniform tariffs, a consumer who takes his maximum load at an off-peak period of the whole undertaking should receive some form of rebate. If such a rebate were adopted it would have a very great effect upon the charges, and would not lend itself to a uniform tariff.

We have a tariff under which the maximum-demand indicator is in gear only during the peak-load period of the undertaking. The effect of such a tariff is to encourage the consumer to reduce his load during the peak period, which enables us more or less to fill up the valleys in the load curve. I have in mind the case of a consumer whose maximum load during 22 hours of the day is 1 000 kVA; during the remaining 2 hours, which is the peak-load period, his maximum load comes down to 50 kVA. We have to measure that, and so far we have not found a satisfactory form of kVA meter which will do so.

Mr. Albert Page: My impression is that, as the supply industry grows older, there is a tendency for tariffs to become more and more involved, and I do not think this position is beneficial to the industry. The more simple we make the tariffs, the higher will be the consumption. The point which we have to watch very carefully is the total amount spent on generation and distribution.

On page 683 the authors say " Unfortunately, no apparatus is manufactured extensively which provides this true maximum demand. . . ." Is not this a very unfortunate position? The authors deal with a case where a 100 per cent. error is readily possible in the maximum demand, and yet they trouble to design instruments to get the error down to ± 2 per cent. I hope meter engineers will put their heads together and think out a device that will overcome this grave difficulty.

Regarding the hold-on and hold-off types of resetting devices, the authors are not quite fair to the hold-on pattern when they say that it is subject to a lot of wear in the bearings. My experience has shown that such wear never occurs in a properly designed instrument.

Turning now to the section which deals with the measurement of power factor (page 685), under (b) the authors refer to " The average power factor of the consumer's load, taken over the same period as the bulk kW maximum demand." Is it their intention to endeavour to apply a tariff of this nature? If so, it seems to me a most serious reversal of our present arrangements. At present we endeavour to estimate when the time of maximum demand occurs on an undertaking. I have known a case where time switches have been set to periods of restricted maximum demand, say, during the afternoon; and unfortunately a snowstorm has occurred in the morning, when the maximum amount of lighting and heating has been on. Thus the maximum demand occurred in the morning, while the time switch measured it in the afternoon. The best way is to have some form of control from the power station, and this is rather a difficult matter. Measurement (c), " The average power

factor of the consumer's load at the time of his kW maximum demand," really gives what we want to know. In another part of the paper the authors mention that, if we know the kVA, we do not require to know the power factor at times of maximum kW demand. This is the wrong way of looking at the problem. No absolutely satisfactory kVA meter has yet been made; but it is possible to use a kWh meter and in conjunction with a sine meter by mechanical means to tell what is the average power factor over the period of maximum kW demand. If this is done one can solve the whole problem without using any extraneous contrivances. The arrangement adopted by the Central Electricity Board, is to compare the simultaneous readings of two maximum demands, and my impression is that it is a very excellent method. That, however, is totally unnecessary with the arrangement to which I have just referred.

Regarding the new type of instrument described by the authors, I notice that they mention as an advantage the fact that there are no extraneous relays. The device at the side, however, can surely be described as such. A further point is that they only show a single-phase relay, but mention that a polyphase relay could be installed if necessary. They should have said " should be installed," not " could be installed." As regards the routine testing, I quite agree that the calibration of the kWh meter might be a simple matter, but I should not like to have to calibrate the power-factor compensator.

I should like to suggest two minor corrections. First, on page 686, under " Measurement of kVA Demand," the author says " There appears to be no single intrument on the market which will register the product of volts and amperes. . . ." I think they should have said " a.c. volts and amperes."* Secondly, on page 683, under heading (1) it is stated that there may be a variation of between 1 125 kW and 1 500 kW for A and B. I have tried to find out where the authors get the figure of 1 125 kW from, but I have not been able to do so. Perhaps they would explain this point, because to my mind the figure should be 750 kW.

Mr. A. J. Gibbons: The trend of the discussion rather suggests that what the supply industry is trying to sell is power factor, whereas surely what we are out to sell is the kilowatt-hour. Can we really say that the power factor is any fault of the consumer? I would instance the case where, at one side of the street, a man has a factory that he runs off the d.c. mains. He extends his factory to the other side of the street, where it happens that there is an a.c. main. He says " Will alternating current make the motors go round?" The supply authority reply " Yes, the motors will go round, but you will have a power factor now; it will mean an additional charge on your bill. If, however, you will talk to one of our manufacturing firms and spend a few hundred pounds, they will put it right for you." This suggests that power factor is a trouble introduced by the supply authorities rather than by the consumer.

The simpler the tariffs, the more electricity we are going to sell. I feel that although allocations of power-factor costs to individual consumers may be justified on academic grounds, yet in the majority of cases they are

* Corrected for the *Journal*.

far more a concern of the supply undertaking and can readily be included amongst the general fixed charges of the system.

Mr. F. C. Knowles: I should like to support the plea for simplicity in tariffs which has been made by previous speakers. Why not do what the water and gas undertakings do—simply measure one quantity?

The authors state that if the voltage were constant we should put in ammeters: they really mean ampere-hour meters. Why not start from that? The current is all that the distribution engineer really wants to measure to determine the cable loading. The consumer would understand this system perfectly, and it would throw back on to the distribution and generating engineers that very important problem of the prevention of variation in the voltage of the supply. If, however, one wants to measure kVA, a volt-hour meter in addition to the ampere-hour will be necessary, and the readings will have to be multiplied together.

Mr. J. W. Carter: The Table on page 690 shows that in the case of consumers A and B with power factors of 0·55 lagging and unity respectively, the product of kW and correction factor gives kVA. The definition of the term Z_3 in the power-factor correction formula is not sufficiently rigid to show whether this condition would hold for all the consumers if their power factors were between unity and 0·5 lagging, but if it did the fact would suggest some simplification of method in dealing with the generality of consumers.

I should think also that the actual cost of supply is made up of so many factors that it is impossible to arrive at anything better than a close approximation, and it seems unnecessary to draw distinctions such as the difference between the vectorial and arithmetical methods of arriving at power factor, especially as large consumers generally have reasonably steady power factors, owing to the multiplicity of units of electrical equipment included in their total load.

It would seem, therefore, that in the majority of cases the costing measurements could very well be made with kWh and kVAR meters and recorders, and, since the resulting tariff would require a knowledge of the consumer's loading conditions at the time of maximum demand on the bulk supply, the consumer's permanent equipment would be of the same nature.

Mr. S. Hunt: It seems very clear that there is still no measuring device for dealing with kVA metering which is as accurate or as easy to handle as the ordinary watt-hour meter.

With regard to the out-of-mesh period in maximum-demand indicators, this can largely be allowed for when calibrating and marking the dials of the demand indicators. In regard to the suggestion that the maximum-demand mechanism should be incorporated in the meter case, this mechanism adds an extra mechanical burden to the meter, and far better accuracy is obtained when the demand indicator is a separate unit. This arrangement also lends itself to much better and quicker calibration—and checking.

I have heard various arguments as to the efficacy of the contact device necessary in the impulsing meter, but since we now have some 30 to 40 such equipments which have been in use for a considerable number of years I feel

quite confident with regard to their behaviour. These maximum-demand indicators are, of course, read weekly, this being necessary where large amounts of money are involved.

Another matter I should like to mention is that all our demand-indicator metering equipments are governed by an external time switch, which allows these meters to be in operation only between the hours of 10 a.m. and 6 p.m. This time has been found from experience to cover any ordinary peak which may occur on our system.

Messrs. W. Casson and A. H. Gray (*in reply*): We are pleased to accede to Mr. Hill's request for a more detailed account of the method of computing equation (2), which we give below.

It will be agreed that the additional cost borne by the supply authority, due to the introduction of a power-
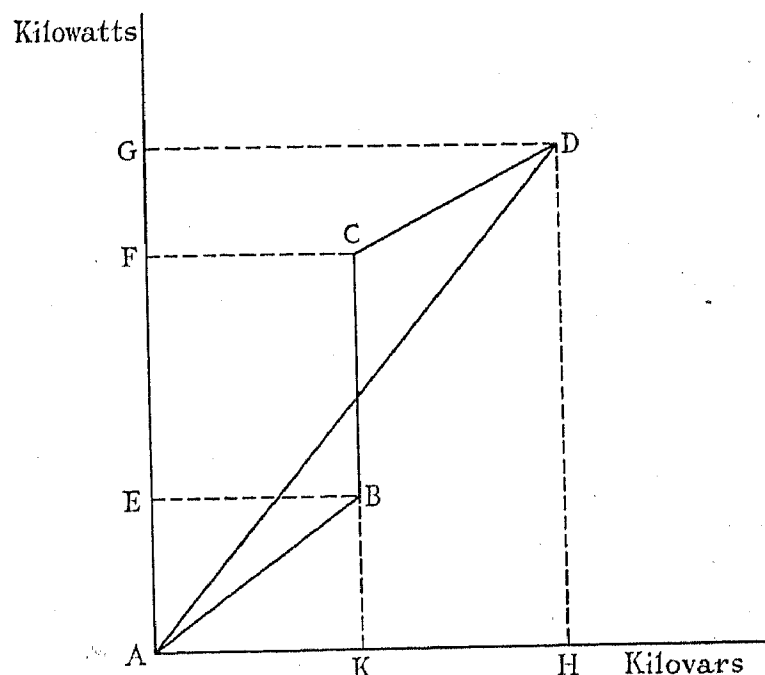
Fig. A

factor clause into the bulk tariff, may be represented by the expression:—

(Bulk kVA demand — Bulk kW demand) × (kW demand charge) × (Correction factor)

where the correction factor is dependent upon the power-factor clause. If this clause is based on the kVA charge, the correction factor will be equal to $1/\cos \phi$.

Since this additional charge is due to the loads of the consumers it would appear that it should be divided amongst those responsible for it, if equality is to be established. Hence, if it is assumed that three consumers represented by AB, BC, and CD (see Fig. A) produce a total bulk kVA demand of AD, and furthermore that the particular tariff operating in this instance is based on a kVA demand charge, then the maximum-demand charge for each consumer can be represented as follows:—

Maximum-demand charge for AB $= EA + X(AD - AG)$

Maximum-demand charge for BC $= EF + Y(AD - AG)$

Maximum-demand charge for CD $= GF + Z(AD - AG)$,

where X, Y, and Z are functions which will produce proportional shares of the additional cost. Furthermore

$$AD = EA + EF + EG + (AD - AG)(X + Y + Z)$$

Hence, to establish this equation,

$$X + Y + Z = 1$$

Since these constants—X, Y, and Z—must be some function of the power factor of the consumer, it can be seen that by making each constant equal to the particular ratio of the consumer's reactive demand to the bulk reactive demand the above equation will be satisfied. That is,

$$X = \text{AK/AH}, \quad Y = 0, \quad Z = \text{HK/AH}.$$

Therefore $\quad X + Y + Z = \dfrac{\text{AK}}{\text{AH}} + \dfrac{\text{HK}}{\text{AH}} = 1$

Hence, if the maximum-demand charge in a bulk-supply tariff, operating with a power-factor clause, can be represented by the expression TbZ_3 (see page 682), the additional charge due to the power-factor clause may be represented by $(TbZ_3 - Tb)$. This additional charge can therefore be divided amongst consumers, in order to establish an equitable allocation, so that each bears a proportion represented by

$$\frac{R_c}{R_b}(TbZ_3 - Tb)$$

Each consumer's contribution to the bulk-supply maximum-demand charges will therefore be represented by YbZ_1; where Z_1, the power-factor correction factor of the consumer's contribution to the bulk-supply power-factor charges, is given by the equation

$$Y_bZ_1 = Yb + \frac{R_c}{R_b}(TbZ_3 - Tb)$$

Hence, by transposition,

$$Z_1 = 1 + \frac{R_cT(Z_3 - 1)}{R_bY}$$

But $\qquad R_c/Y = \tan \phi_c, \quad \text{and} \quad T/R_b = 1/\tan \phi_b$

Hence $\qquad Z_1 = 1 + \dfrac{\tan \phi_c}{\tan \phi_b}(Z_3 - 1)$

Replying to Mr. Hill's comments concerning the pendulum type of clock, we would point out that such a system need not necessarily have a time-period which coincides with the peak load and hence cannot be regarded as a true maximum-demand meter. On the other hand, since the Central Electricity Board use the definite-period time system it becomes necessary to adopt a similar system for the metering of large consumers, if errors due to diversity are to be eliminated and a true cost established.

We agree that an ammeter cannot be scaled in kWh and hence would not serve as a demand indicator; the ammeter mentioned in the paper was given as an illustration before passing to the Ferraris-motor type, which includes the necessary measure of time.

Dealing with the question of rectifiers and d.c. instruments, we are particularly interested in Mr. Hill's comments concerning the errors due to ripples in the supply, and agree that the meter will only integrate the power in the ripple accurately if the current through the meter is in phase with the main current and the

current through the voltage coil is in phase with its voltage, or if the phase displacements in each case are similar. If these conditions can be obtained, then the meter will measure accurately.

Referring to the delta-connected network, we would apologize for the paucity of the description and would extend it as follows: In Fig. B, let AB, AC, and BC represent the voltage vectors of the 3-phase input. Let $AD = E_1F_1 = E_2F_2$, etc., in magnitude but displaced one from the other by 10°. Then $E_1H/E_1B = \sin 60°$, and $E_1H/E_1F_1 = \sin 80°$.

Therefore $\quad BE_1 = E_1F_1 \sin 80°/\sin 60° = k \sin 80°$

Similarly $\quad BE_2 = E_2F_2 \sin 70°/\sin 60° = k \sin 70°$,

and $BE_3 = k \sin 60°$, $BE_4 = k \sin 50°$, $BE_5 = k \sin 40°$, $BE_6 = k \sin 30°$.

The question of unbalance and the single-phase power-factor relay element, raised by Mr. Hill, appears to have
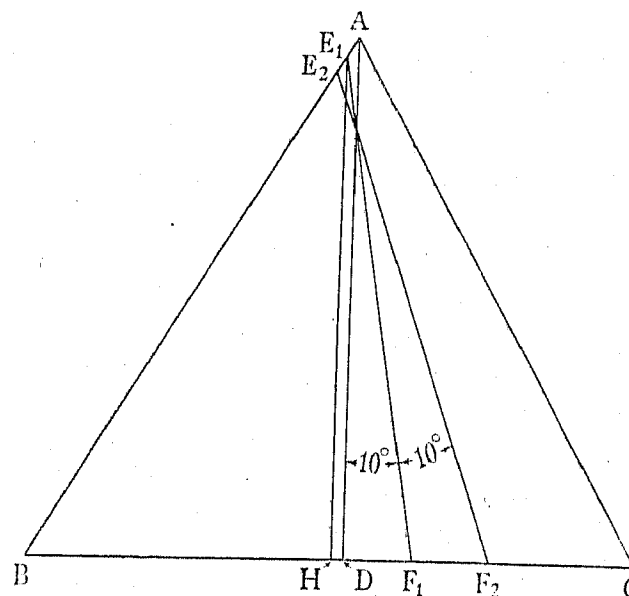
Fig. B

given rise to a certain amount of general discussion, and this point is dealt with in full in our reply to Mr. Byrne.

We would assure Mr. Hill that the equipment is not expensive as he surmises, and furthermore that it is perfectly satisfactory for use on any installation either large or small, if kVA demand is required. Since, however, the paper was primarily confined to the measurement of large supplies, we did not discuss the use of the particular instruments on small installations.

Mr. Spilsbury raises a question concerning the inaccuracy of maximum-demand indicators; we actually had in mind indicators having a scale diameter of 5 in. or more, such as is usual in most modern designs. Referring to the multi-turn indicators such as are generally fitted to summators employing some form of impulsing gear, we do not think that the error introduced by misplaced impulses can be regarded as unduly serious. For mechanical reasons it is usual to limit the size of the impulse to 1/1 000th part of the full-scale reading of the demand indicator. Furthermore, it is usual to arrange for the speed of impulsing to be such that only one impulse will be missed during a reset period, which will thus produce an error of 0·1 per cent of full-scale reading. This assumes that the summators are not

fitted with compensation; but the fact that compensation is generally fitted to all multi-turn indicators means that this particular error will again be materially decreased.

As is stated in the paper, the kVAh meter is not a new idea. Actually a meter known as the Esterline–Angus volt-ampere-hour meter was brought out in the U.S.A. some years ago, but we are unable to say whether it has ever become a practical proposition. This particular meter used a phase-shifter rotor as its voltage electromagnet, as compared with the delta-connected network used by us, and, whilst the phase-shifter would provide finer subdivisions, it was felt that the high driving torque required and the uneven voltage distribution around the travel introduced more practical difficulties and errors than the method described in the paper.

We agree with Mr. Spilsbury's solution for the deter-.

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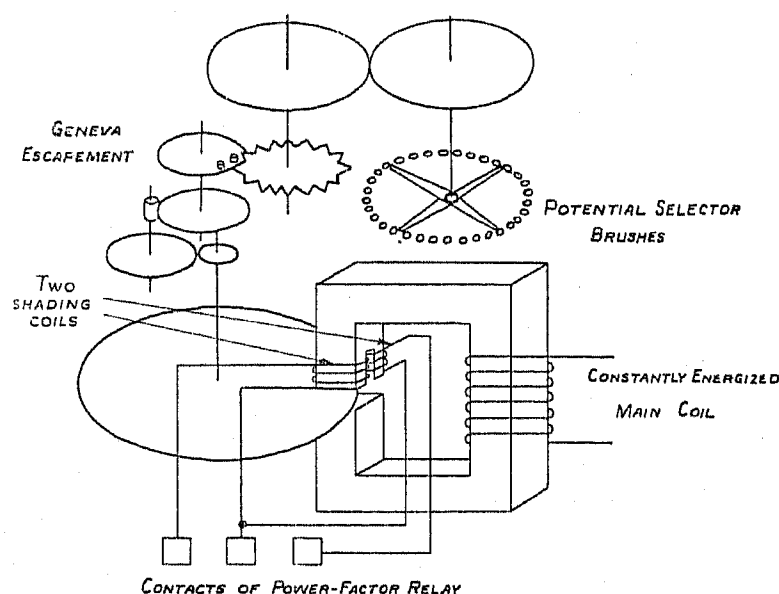
Fig. C.—Ferraris-motor drive.

mination of the network values, and would refer him to the proof given in our reply to Mr. Hill's query.

With regard to the question of the voltage impressed upon the measuring instrument, should it be considered undesirable to calibrate for the special voltage, i.e. $\sqrt{3}/2$ line voltage, small transformers could be inserted to restore the voltage to its original value. At the same time we would point out that, as is suggested in the paper, the use of auto-transformers in place of resistances eliminates this difficulty.

The method adopted to ensure correct operation of the power-factor relay at low loads, without undue hunting at high loads, is to use a high number of series ampere-turns in conjunction with a rotor of high conductivity. At the same time the "bouncing" of the contacts on high loads is eliminated by the use of very flexible contacts in conjunction with suitable location stops on the rotor itself.

The special gearing for obtaining quick movement between studs is illustrated in Fig. C. It will be seen that the duo-velocity movement is obtained by the standard pin and star-wheel combination often used in meter work.

We regret that Mr. Byrne has obtained the impression that we assume future tariffs will be fixed on a kVA

basis. That it was not our intention to convey such a meaning is confirmed by the fact that no mention was made of any particular type of power-factor clause. The object of the first part of the paper was to put forward a suggested method for obtaining the actual cost of a load, to serve as a basis for checking the charge under the particular existing tariff. We consider that in order to obtain this cost it is necessary to measure the kVA demand, but we do not advocate in the paper the use of kVA as a basis for a tariff. We are not altogether in agreement with Mr. Byrne when he states that commercial adjustments of power factor are becoming of diminishing importance. The absence of a power-factor clause from the bulk-supply tariff may make little difference to the question of whether a consumer should be charged on the kVA basis, since the cost of distribution may be of greater importance than the cost of production, depending upon the loading of the plant, which is governed to a considerable extent by power factor. As a matter of interest, the national tariff itself is quite applicable to our method of costing; the formula for ascertaining the correction factor to the consumer's kW demand at the time of bulk maximum kW demand would be:—

$$Z_1 = 1 \pm \frac{\tan \phi_c}{\tan \phi_b}\left[\left(\frac{0\cdot 85 - \cos \phi_b}{0\cdot 1}\right)\frac{c}{b}\right]$$

where c = power-factor cost per kW of bulk maximum demand, and b = cost per kW of bulk maximum demand.

We agree with Mr. Byrne's comments regarding the danger of the condition of leading power factor, but would point out that our suggested method of costing actually caters for such a condition. We state in the paper that, when the cost of a consumer's load is being ascertained, should the consumer's power factor be leading when the bulk power factor is lagging, then the cost will be decreased. If, however, the bulk-supply power factor is leading, then the cost will be increased. In other words, the costing method will operate in the direction of ensuring unity power factor, which we consider is the ideal condition. Mr. Byrne states that the kVA meter possesses one drawback, which is common to all devices employing a cross-phase system of obtaining voltage displacement, namely response to the negative phase-sequence component in the wrong sense. Whilst this assertion is substantially correct, it should be pointed out that the error under practical conditions is small, as is exemplified by the large number of equipments in service using some form of phasing transformer. The actual test recorded in the paper was carried out using voltmeters and ammeters as standards in order to obviate any question of phase angle. Furthermore, it was made with unsymmetrical voltages, to establish the order of the errors which could be expected with such a network. With regard to the question of unsymmetrical currents, it was fully realized that errors can arise in the power-factor relay itself, but, as is mentioned in the paper, these can be entirely obviated by the use of a polyphase power-factor relay element if the unbalance in the system merits it.

The unbalanced load condition in a 3-phase 3-wire system which has the largest proportion of negative phase-sequence component, is a single-phase load

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between two phases where the negative and positive phase-sequence components are equal in magnitude. Under such loading conditions it is obvious that a polyphase relay system will be necessary to provide true registration. Under the conditions met with in practice, however, it will be realized that the resulting error is of no serious importance.

We thank Mr. Byrne for pointing out an error in the advance copies of the paper. This has been corrected for the *Journal*.

We would inform Mr. Petch that the burden of the delta-connected network is approximately 30 VA per phase.

It is interesting to note the method adopted by Mr. Pitt to overcome the diversity error. Such a method assumes an intimate knowledge of loading conditions; should this knowledge not be available, the method we mention in the paper of using recording apparatus is at present the only available solution.

Mr. Page confirms our impression concerning the intricacies and multitudinous variations of modern tariffs, and he is probably quite right in his statement that a simple tariff would result in a higher consumption. We would point out, however, that simplicity can only be obtained by a careful review of load demands over a considerable period, taking into account a possible increase of load due to this simple tariff. Furthermore, the introduction of a simple tariff can only be economically sound if an accurate knowledge of the actual cost of the supply is available. As is stated in the paper, our method is not intended as a tariff but simply as a basis of a cost upon which a tariff can be made. We do not see Mr. Page's point concerning the method of controlling the time-period from the power station, which we agree must introduce complications. The method of recorders surely provides all the necessary information concerning the diversity without this additional complication.

Mr. Page has evidently misread our statement, under the heading "Measurement of Power Factor," to the effect that it is not necessary to know the average power factor of the consumer's demand at the time of his kW maximum demand if the consumer is charged on a kVA basis. By this, it is implied that the information is not necessary either for ascertaining the true cost of his supply or for use with a standard tariff.

We are afraid that the whole problem cannot be solved as simply as is suggested by Mr. Page when he states that

the kWh meter, together with a device for obtaining the average power factor over the period of maximum kW demand, provides a complete solution. It should be remembered that diversity will still introduce errors.

It is regrettable, as Mr. Page suggests, that no true maximum-demand mechanism is yet available, but at the same time the system of true maximum demand would need the introduction of further complications to obviate diversity errors.

He suggests that we are too severe in our criticism of the "held on" demand indicator; a constantly energized coil, particularly on an alternating-current circuit, must be subject to more vibration than one which is intermittently energized, and hence the wear must be increased. We do consider, however, that this particular trouble is minimized in modern designs.

We would assure Mr. Page that the calibration of the compensator is quite a simple matter, since it consists of checking a series of resistance values only.

With reference to his difficulty concerning Fig. 2, we would remind him that a demand figure of 750 kW necessitates a demand of 1 500 kW in the next period. If, however, the period is taken from 1 hour $7\frac{1}{2}$ minutes to 1 hour $37\frac{1}{2}$ minutes, etc., individual demands of 1 125 kW are obtained as stated in the paper.

We agree with the remarks of Mr. Gibbons and Mr. Knowles concerning the question of simple tariffs.

We would inform Mr. Carter that the correction factor mentioned in the Table is obtained from the factor $(R_c/R_b)/(TbZ_3 - Tb)$. In the case of a tariff operating on a kVA basis this factor would become $(R_c/R_b)(Kb - Tb)$ where K is the maximum demand in kVA.

Mr. Hunt is apparently still waiting for the kVA meter which will have the good properties of the present induction watt-hour meter. Such an instrument would be very simple to design if the product of a.c. volts and a.c. amperes could be integrated without the interference of the phase angle between them. In the present state of the art, however, this integration is unfortunately impossible without the use of extraneous devices, and we suggest that the method we have adopted—to keep the voltage and current in a constant phase relationship—is theoretically sound.

Referring to the errors due to the reset period, we agree that these can be reduced to fine limits by the introduction of some form of compensation.

THE SPACING/HEIGHT RATIO OF LIGHTING UNITS*

By H. R. S. McWHIRTER, B.Sc.(Eng.), Associate Member.

SUMMARY

In the present paper a method of evaluating the light-dispersing power of a light source is given, together with methods of calculating suitable values of spacing/height ratio from the polar distribution curve of the source. Optimum polar distribution curves corresponding to certain values of spacing/height ratio are shown, and information is given from which the optimum polar distribution curve corresponding to any value of spacing/height ratio may be drawn. A new criterion applicable to polar distribution curves and indicating their suitability for producing uniform illumination is suggested. New methods of testing lighting fittings are described. Suggestions are also made relative to the preparation of technical literature on the subject.

(1) INTRODUCTION

Some light sources, notably certain of those used for lighting roads, emit the major part of their light in directions approaching the horizontal. Others, such as those used for interior illumination and known as the "concentrating" type, emit most of their light in directions much nearer the vertical. A need therefore exists for some method of evaluating the extent to which a light source spreads or disperses its light. Such a method is developed below.

Closely associated with this is the question of the spacing/height ratio at which the light source should be used. A method of calculating this from the polar distribution curve is also given.

Optimum polar curves, for values of spacing/height ratio of 1, 1·5, and 2 respectively, are given together with information from which the optimum polar distribution curve for any other value of spacing/height ratio may be constructed. These polar curves should be of use to designers of lighting fittings.

The other suggestions put forward relating to the comparing and testing of practical lighting units, are based on data obtained from the optimum curves and from the previously-developed theories.

(2) EVALUATION OF LIGHT-DISPERSING PROPERTIES OF LIGHT SOURCES

Let Fig. 1 represent a light source at O, suspended at a height h vertically above a horizontal plane SP. Let ONQR be the polar distribution curve of the light source. Consider the point P situated at a distance l from the point S, the latter point being vertically under the light source. Then when h is zero the illumination at P will be zero. Also when h is infinite the illumination

at P will be zero. Hence there must be some finite value of h for which the illumination at P will be a maximum. Also any change in the distance l would have to be accompanied by a proportional change in h to maintain maximum illumination at P. Therefore the angle POS
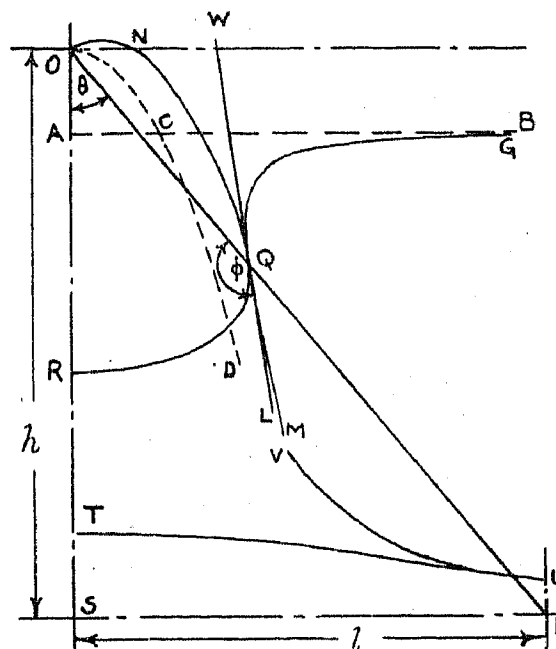
Fig. 1

would be invariable during these changes and its value may be found as shown below.

Let θ = angle POS, I = candle-power OQ, and E = illumination at P.

Then

$$E = \frac{I}{h^2} \cos^3 \theta \qquad \cdots \quad (1)$$

But

$$h = \frac{l}{\tan \theta}$$

Hence

$$E = \frac{I}{l^2} \tan^2 \theta \cos^3 \theta$$

$$= \frac{I}{l^2} \sin^2 \theta \cos \theta \qquad \cdots \quad (2)$$

Since l is to be considered fixed, E will have a maximum value when the function $I \sin^2 \theta \cos \theta$ has a maximum value. Suppose this occurs when $\theta = \mu$, $I = I_\mu$. Then the maximum value of E will be $\frac{I_\mu}{l^2} \sin^2 \mu \cos \mu$.

The value of the angle μ will now be found for three well-known polar curves.

In Fig. 2 the semi-circle represents the polar curve of a uniform point source situated at O. In this case

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I is constant, and the differential coefficient of $I \sin^2 \theta \cos \theta$ with respect to θ is $I(2 \sin \theta \cos^2 \theta - \sin^3 \theta)$. This expression vanishes when $\theta = 0$ or $\theta = \arctan \sqrt{2}$. The latter value of θ makes $I \sin^2 \theta \cos \theta$ a maximum. Hence in this case $\mu = \arctan \sqrt{2} = 54°\ 44'$ approximately. A radius vector at this angle is shown in Fig. 2.

Fig. 3 shows the polar curve of a disc source situated at O. The source is assumed to be a horizontal flat disc of small size facing downwards and emitting light as a perfectly diffusing surface. The polar curve is a circle with O on its circumference and with its centre on a perpendicular dropped from the flat disc. If I_0 is the candle-power vertically downwards, then $I = I_0 \cos \theta$ and

$$I \sin^2 \theta \cos \theta = I_0 \sin^2 \theta \cos^2 \theta$$
$$= \tfrac{1}{4} I_0 \sin^2 2\theta$$

The differential coefficient with respect to θ of the right-hand side of this equation is $\tfrac{1}{2} I_0 \sin 4\theta$, which is zero when $\theta = 0$ or $\theta = \pi/4$. The latter figure refers to a maximum, and therefore $\mu = \pi/4$ radian $= 45°$ in this
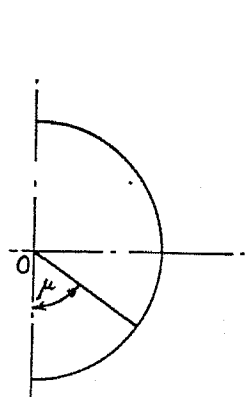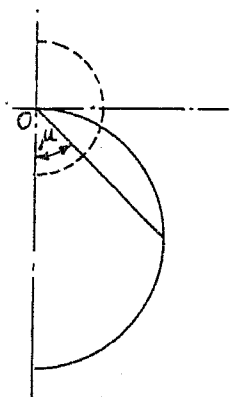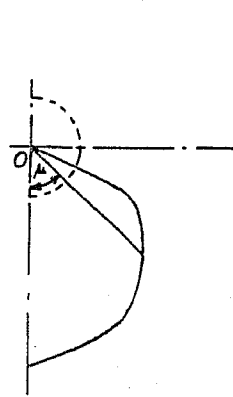
Fig. 2.   Fig. 3.   Fig. 4
$\mu = \arctan \sqrt{2}$. $\mu = 45°$. $\mu = 46°\ 30'$.

case. A radius vector at this angle is shown. A dotted semi-circle representing mean spherical candle-power is also shown; its radius is $I_0/4$.

Fig. 4 shows the polar curve* applying to the well-known Industrial Reflector Fitting No. 1, standardized in B.S.S. No. 232—1935. The value of μ in this case has to be found graphically. A suitable method is to plot values of $I \sin^2 \theta \cos \theta$ as ordinates against values of θ as abscissæ, and ascertain the value of θ for which the function is a maximum. By this method the value $46°\ 30'$ is obtained, and this is therefore the value of μ. In Fig. 4 a radius vector is drawn at this angle. A dotted semi-circle representing mean spherical candle-power is also drawn. Its radius is equal to the vertical radius vector of the polar curve divided by $4\cdot5$.

The practical utility of a knowledge of the value of the angle μ for a particular polar curve may be realized from the following considerations. Imagine a horizontal circular area illuminated from a light source suspended vertically above its centre. The illumination at the circumference would be a maximum when a radius of the circle subtended the angle μ at the light source. Therefore in this instance a knowledge of μ affords a

* This curve is reproduced by permission of the Controller of H.M. Stationery Office. It is taken from Technical Paper No. 3 of the Department of Scientific and Industrial Research, entitled " Light Distribution from Industrial Reflector Fitting No. 1 (British Engineering Standard)."

means of finding what is, from one point of view, an optimum suspension height for the light source. When to this is coupled the fact that light sources which " concentrate " the light have in general smaller values of μ than those which " spread " it, it seems reasonable to use this angle as a measure or indication of the light-dispersing power of light sources. The name " dispersive angle " suggests itself as suitable for this angle, and will hereinafter be used.

Referring again to Fig. 1, it has been postulated that the function $I \sin^2 \theta \cos \theta$ should have its maximum value when $\theta = \mu$ and $I = I_\mu$. Hence the condition

$$I \sin^2 \theta \cos \theta \not> I_\mu \sin^2 \mu \cos \mu \quad . \quad . \quad . \quad (3)$$

applies to the polar curve in this figure. $I_\mu \sin^2 \mu \cos \mu$, however, is a constant, and denoting this by A we have

$$I \sin^2 \theta \cos \theta \not> A \quad . \quad . \quad . \quad . \quad (4)$$

Therefore no radius vector in the polar curve can exceed in length the radius vector at the same angle of the curve given by

$$I \sin^2 \theta \cos \theta = A$$

or

$$I = \frac{A}{\sin^2 \theta \cos \theta} \quad . \quad . \quad . \quad (5)$$

The curve GQM in Fig. 1 is part of the locus given by this last equation. From the above arguments it must lie entirely on that side of the polar curve ONQR which is remote from the origin, and both it and curve ONQR must pass through the point $Q(I_\mu, \mu)$. Therefore the two curves would have a common tangent at Q unless the curve ONQR happened to have a cusp at that point. This common tangent is shown in Fig. 1 as the line WQL. Incidentally, the radius vector OQ in Fig. 1 is drawn at the correct dispersive angle, and therefore the angle θ shown in that figure has the particular value μ.

It should be noted that the curve ONQR may be altered in shape, without the value of the dispersive angle μ being altered, provided that the modified curve, when drawn to such a scale as to pass through the point Q, does not cross the curve GQM. Inspection of Fig. 1 shows that this property permits a very wide modification of the curve ONQR while the same value of dispersive angle is retained.

If the polar curve of the light source was the curve GQM the light source would have the remarkable property that the illumination produced at every point on SP would be independent of the value of h. For, from equation (2),

$$E = \frac{I}{l^2} \sin^2 \theta \cos \theta$$

But

$$I = \frac{A}{\sin^2 \theta \cos \theta}$$

Hence

$$E = \frac{A}{l^2} \quad . \quad . \quad . \quad . \quad . \quad (6)$$

This shows that E would be independent of h and inversely proportional to the square of the value of l.

The curve UV in Fig. 1 shows E plotted as ordinate to a base of l. The curve UT in Fig. 1 also shows the same thing, but with reference in this case to ONQR as the

polar curve. Obviously the curves UT and UV will have a common tangent at U, and UT must always be below UV. The slope of the common tangent at U will be given by

$$\frac{dE}{dl} = -\frac{2A}{l^3}$$

$$= -\frac{2E}{l} \qquad . \quad . \quad . \quad . \quad (7)$$

Curves such as UT and UV (Fig. 1), will be hereinafter referred to as "contour illumination curves."

A certain geometrical condition that sometimes obtains when the illumination at P is a maximum may be found by differentiating both sides of equation (2). We have

$$\frac{dE}{d\theta} = \frac{1}{l^2}\left(-I\sin^3\theta + 2I\sin\theta\cos^2\theta + \sin^2\theta\cos\theta\frac{dI}{d\theta}\right)$$

For a maximum, minimum, or stationary value of E, the expression in brackets must equal zero. This gives, when simplified, $\sin\theta = 0$ or

$$\frac{1}{I}\frac{dI}{d\theta} = \tan\theta - 2\cot\theta \quad . \quad . \quad . \quad . \quad (8)$$

But

$$\frac{1}{I}\frac{dI}{d\theta} = \cot\phi$$

where ϕ is the angle OQL (Fig. 1).

Hence $\tan\theta - 2\cot\theta = \cot\phi$.   .   .   (9)

This condition would necessarily apply when E had a maximum value provided that the curve ONQR did not have a cusp at Q. It would also apply when E had a minimum or stationary value, and it is not of much practical use in finding the value of the dispersive angle. The condition is merely noted here as being of theoretical interest. It may be mentioned that the curve of equation (5) (GQM in Fig. 1) obeys this condition at every point on its length. The remaining properties of the curve GQM are as follows:—

(i) There are two asymptotes, namely the straight line $I = A/\cos\theta$ (ACB in Fig. 1) and the parabola $I = A\cos\theta/\sin^2\theta$ (OCD in Fig. 1).

(ii) The radius vector of the curve at any angle θ is the sum of the radii vectores of these two asymptotes at that angle.

(iii) There is a point of inflexion at $\theta = 30°$, $I = A \cdot 8\sqrt{3}/3$.

(iv) The slope of the curve is vertical at $\theta = 45°$, $I = 2\sqrt{2}A$.

(v) The minimum value of I is $A \cdot 3\sqrt{3}/2$, occurring when $\theta = \arctan\sqrt{2}$.

(vi) The curve does not possess a dispersive angle.

It would be impossible to make a light source having this curve as its polar curve, if only because the quantity of light emitted would require to be infinite.

(3) CALCULATION OF VALUES OF SPACING/HEIGHT RATIO

In Fig. 5, let L_1 and L_2 represent two light sources suspended at the same height above a horizontal plane SH. The spacing/height ratio in such a case is usually taken to be the ratio SH/HL$_2$. If the distance SH is regarded as fixed, the illumination at P will be a maximum when the angles PL$_1$S and PL$_2$H are equal to the dispersive angle. Hence the value of spacing/height ratio under these conditions would be $2\tan\mu$.

In Fig. 6 let L_1, L_2, L_3, and L_4 represent four light sources in plan at the corners of a square, P being the centre of the square. In this case it is common practice to define the spacing/height ratio as
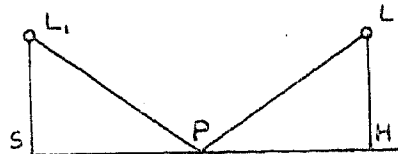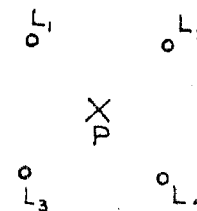
Fig. 5   Fig. 6

$$\frac{\text{Length of side of square}}{\text{Mounting height of light sources}}$$

Regarding the size of the square as fixed, the illumination at P would be a maximum when the semi-diagonal such

Table 1

Source	μ	$2\tan\mu$	$\sqrt{2}\tan\mu$
Uniform point source (Fig. 2) ..	54° 44′	$2\sqrt{2}$	2
Disc source (Fig. 3)	45°	2	$\sqrt{2}$
Industrial Reflector Fitting No. 1 (Fig. 4)	46° 30′	2·11	1·49

as PL$_1$ subtended the dispersive angle at the corresponding light source L_1. This would occur when the spacing/height ratio defined as above had the value $\sqrt{2}\tan\mu$.

Applying these formulæ for spacing/height ratio to the
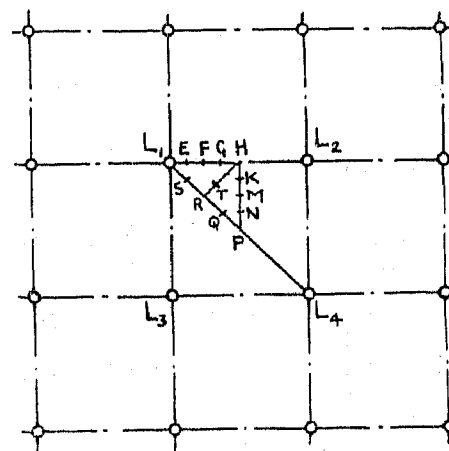
Fig. 7

three polar curves considered in Section (2), the values given in Table 1 are obtained.

The values given in the final column agree with the values that are generally considered to embody good practice at the present day, for the respective light sources. At present, however, these values are arrived

at from considerations of uniformity of illumination and practical expediency. It is therefore of great interest to see the same values result when a totally different line of investigation is followed.

In the case of a large installation having the light sources arranged as in Fig. 7, in which the light sources are indicated by small circles, the value of spacing/height ratio may still be taken to be $\sqrt{2} \tan \mu$. This is because with such an installation it is often necessary to illuminate a local part of the plane from the four light sources immediately above it, and then the conditions are identical with those indicated in Fig. 6.

(4) OPTIMUM POLAR DISTRIBUTION CURVES

It has been shown in Section (2) that the polar curve of a light source may be modified through wide limits without altering its dispersive angle, provided that certain conditions are observed. The question therefore arises whether the polar curve can be so modified that uniform illumination is produced on the plane below, when the light sources are suspended at the optimum height.

In attempting a solution of this problem it has been assumed that the uniform illumination is produced by a large installation having the light sources at the corners of squares, as in Fig. 7. The question resolves itself into finding the contour illumination curve that one light source must produce on the plane, in order that the illumination thereon due to all the light sources may be uniform.

This contour curve is shown in Fig. 8 as the curve TUH. It was found by a process of trial and error as follows. A baseline SH was drawn representing to scale the distance L_1L_4 in Fig. 7. It was bisected at P and the perpendicular PU erected of unity length, representing the value of illumination at P due to light source L_1. The value of this illumination was assumed to be unity. A perpendicular HE, also of unity length, was dropped from H. The line EU was drawn, and produced to F. Then, from equation (7), the straight line EUF is the tangent at U to the required contour curve. The curve KUV was also drawn passing through U and having ordinates inversely proportional to the square of the abscissæ. Then, from the discussion in Section (2), the required contour curve cannot lie above this curve at any point but must touch it at U.

A trial contour curve was then sketched in, and the illumination that it would produce at points L_1, E, F, G, H, K, M, N, P, Q, R, S, and T (Fig. 7) was ascertained. With regard to these points it may be mentioned that they divide the lines L_1H, HP, and PL_1 respectively into four equal parts, and T is the centroid of the triangle L_1HP. These points will be hereinafter referred to as "test points."

The trial contour curve was then modified until the values of the illumination at the test points became as nearly equal as possible. The contour curve TUH (Fig. 8) was finally reached, the values of the ordinates being shown at the feet of the ordinates, which are equally spaced along the baseline SH. It is noteworthy that for a considerable part of its length the contour curve is indistinguishable from the tangent FUE. Since the curve reaches zero at H, only the four light sources L_1, L_2, L_3, and L_4 (Fig. 7) can be producing illumination at

P, and hence the value of this illumination must be 4. The values at the other test points are: L_1, 4; E, 3.995; F, 3.91; G, 3.925; H, 4; K, 3.97; M, 3.95; N, 3.98; P, 4; Q, 3.98; R, 3.89; S, 3.96; T, 3.93. From these figures the maximum illumination is seen to be 4 and the minimum 3.89. Since the latter value is 97.25 per cent
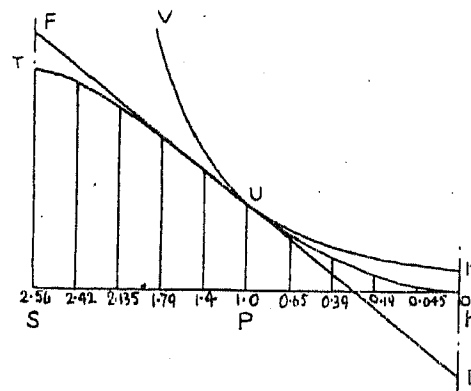
Fig. 8

of the former, this constitutes what is practically uniform illumination.

The contour curve in Fig. 8 having been obtained, it is an easy matter to produce optimum polar curves corresponding to any value of the spacing/height ratio. All that is necessary is to assume that the contour curve is produced by a light source suspended at a height $\sqrt{2}(l/n)$ above the point S; where l is the length SP and n is the spacing/height ratio. The polar distribution curve may then be plotted by the use of equation (1).

In Fig. 9, three optimum curves are shown correspond-
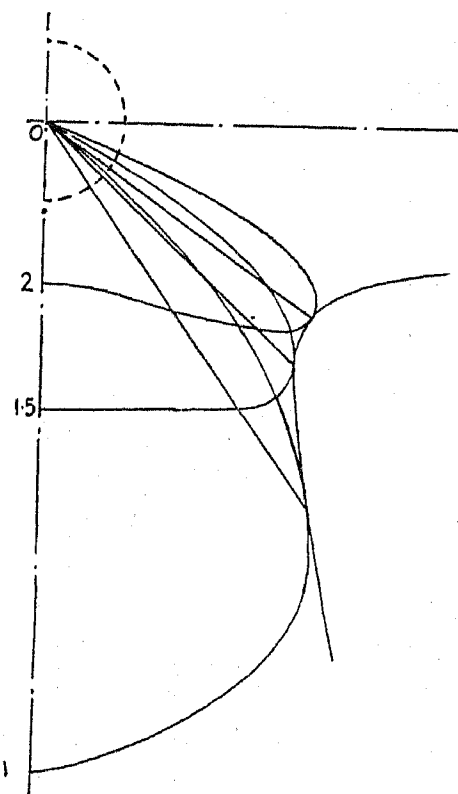
Fig. 9

ing to values of spacing/height ratio of 1, 1.5, and 2 respectively (written against the curves). All the curves have the same value of mean spherical candle-power, and this is indicated by a dotted semi-circle. Radii vectores are drawn at the respective values of dispersive angle. A curve corresponding to equation (5) and touching all three

optimum curves is also shown. This curve would form the envelope of all the optimum polar curves having the same value of mean spherical candle-power.

In these optimum curves there is a certain minimum value of θ above which no light is emitted. The complement of this angle is usually known as the angle of cut-off. Its value in the present curves is arc $\tan \sqrt{2}/(2n)$, where n is the value of spacing/height ratio. The dispersive angle μ is, of course, given by arc $\tan n\sqrt{2}/2$, since $n = \sqrt{2} \tan \mu$. The values of these two angles are given in Table 2 for the three curves shown in Fig. 9. These values of the angle of cut-off are high in comparison with those encountered in practical reflectors. The angle of cut-off in Industrial Reflector Fitting No. 1, which has a value of dispersive angle of 46° 30', is 20°. A high value for the angle of cut-off is, however, an advantage, if it can be obtained without sacrifice of efficiency.

A great disparity is evident between the optimum curve marked 1·5 (Fig. 9) and that of Industrial Reflector Fitting No. 1, which is shown in Fig. 4, and which has

Table 2

Spacing/height ratio	Dispersive angle	Angle of cut-off
1	35° 16'	35° 16'
1·5	46° 40'	25° 13'
2	54° 44'	19° 28'

practically the same value of dispersive angle. A still greater disparity is evident between the optimum curve 2 and the curve in Fig. 2. Optimum curve 1, however, is not unlike that obtainable from certain " concentrating " type fittings on the market. The general conclusion may be drawn that the difficulty of constructing a light source having an optimum distribution curve would be greater at the higher values of spacing/height ratio.

It has been shown in Section (3) that when light sources are arranged as in Fig. 5 the spacing/height ratio should be $2 \tan \mu$. It is therefore necessary to investigate the distribution of illumination obtainable from two light sources having optimum polar curves when suspended at this value of spacing/height ratio.

This distribution of illumination is shown by curve TU_1T_1 in Fig. 10, and it was obtained by adding the ordinates of two of the contour curves TUH in Fig. 8. The maximum illumination is 2·56 and the minimum 2, i.e. 78 per cent of the maximum value. This percentage would remain unaltered if instead of two light sources there were any greater number in the same straight line and at the same distance apart. Therefore the optimum polar curves not only produce uniform illumination when the light sources are arranged as in Fig. 7, but they give a satisfactory degree of uniformity when the light sources are arranged in a single row at the correspondingly increased value of spacing/height ratio.

In practice it would be a formidable task to produce a light source having a polar curve agreeing precisely with

one of the optimum curves. It is therefore desirable to know which particular property of the optimum curve designers of lighting fittings should endeavour to reproduce in practice. There can be little doubt that one of the most important properties is the relation between the candle-power in the direction of the dispersive angle and that vertically downwards. These two values of candle-power chiefly determine the illumination at points P and L_1 respectively (Fig. 7); and in practice it is usually these two points that have the greatest difference in illumination. The two values of candle-power should therefore be such that they produce illumination on the plane proportional to UP and TS respectively in Fig. 8.

But
$$\frac{TS}{UP} = \frac{I_0}{I_\mu \cos^3 \mu} = 2 \cdot 56$$

In a practical polar curve, therefore, the value of the ratio $I_0/(I_\mu \cos^3 \mu)$ may be taken as an approximate indication of the suitability of the polar curve for producing uniform illumination; the nearer this is to 2·56 the better will be the polar curve. Its values for the three sources considered in Section (2) are as follows: Uniform point
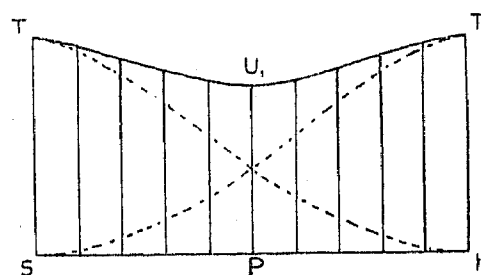
Fig. 10

source, 5·2; disc source, 4; Industrial Reflector Fitting No. 1, 4·3. The polar curve of the disc source is therefore the best of these for producing uniform illumination.

(5) TESTING OF LIGHTING FITTINGS

It would be a very simple matter to find experimentally the dispersive angle, and also the ratio $I_0/(I_\mu \cos^3 \mu)$, without reference to the polar curve. The procedure, in brief, would be as follows. Referring to Fig. 1, a portable photometer would be placed at P with its registering surface horizontal, and the light source O would be raised or lowered in the vertical line OS until the photometer indicated maximum illumination. The dispersive angle would then be given by $\tan \mu = PS/SO$. The ratio $I_0/(I_\mu \cos^3 \mu)$ could then be found by dividing the value of illumination at S by that at P.

(6) PREPARATION OF TECHNICAL LITERATURE

Polar curves for lighting fittings are frequently published without a scale being assigned to them. This is sometimes for the reason that the curve in question applies to a range of similar fittings of various sizes. Such curves might advantageously have superimposed on them the semi-circle representing mean spherical candle-power, as has been done in Figs. 3, 4, and 9. This would facilitate finding the scale of the curve for a particular fitting, as the radius of the semi-circle would be proportional to the mean spherical candle-power of the lamp

inserted multiplied by the efficiency of the fitting. The radius vector at the dispersive angle might also be indicated with advantage on all polar curves.

(7) CONCLUSIONS

The foregoing suggestions would lead to two new criteria being applied to lighting units: namely the dispersive angle, conveying an idea of the light-spreading properties of the unit and furnishing a means of calculating the spacing/height ratio at which it should be used; and the ratio $I_0/(I_\mu \cos^3 \mu)$, conveying an idea of the suitability of the polar curve for producing uniform illumination. The optimum polar curves in Fig. 9 would serve as a complete standard of comparison in this respect.

Further investigation might profitably be made into the light distribution obtainable from light sources having the optimum polar curves but suspended in formations different from that shown in Fig. 7, and at values of spacing/height ratio other than that corresponding to the respective polar curves. Similar investigations in connection with Industrial Reflector Fitting No. 1 have already been made by the author.*

* *Journal I.E.E.*, 1930, vol. 68, p. 1012; also *Journal of the Royal Technical College, Glasgow*, 1932, vol. 2, p. 688.

DISCUSSION ON

"DESIGN DATA IN RURAL DISTRIBUTION LINES"*

NORTH MIDLAND CENTRE, AT LEEDS, 12TH NOVEMBER, 1935

Mr. W. H. C. Pilling: I notice that the author says that the cost of steel or reinforced-concrete masts or poles is from 10 to 15 per cent more than that of wood poles. In the development of a certain rural area which is now taking place a very large amount of arable country has to be crossed, and unusual wayleave difficulties were anticipated. To meet these anticipated difficulties it was decided to endeavour to produce a steel mast which would compete with the wood pole, and this has been done by the introduction of a longer span length. Instead of the usual 350- to 400-ft. span, one of approximately 600 ft. has been employed. I admit that this system would not be economic in any but a flat district. The advantages claimed are several. First of all, there is a reduction in the number of supports and, consequently, in the number of insulators, which are generally admitted to be a potential source of breakdown. There is also a reduction in the cost of wayleaves, and a much greater ease in obtaining them. With the 600-ft. span it is possible to span a larger number of fields than with ordinary poles. The new system also avoids a number of appeals to the Minister of Transport, which are the cause of much delay and trouble. Finally, steel is a British product, whereas the majority of the wood poles used for overhead-line construction are imported from abroad. A point that may be raised against this type of construction is the difficulty of erection. This has been overcome by the use of a 6-wheel lorry fitted with a mechanical winch. The lorry can also be used for transporting the masts to the site and for pulling up the conductors to the correct sag.

The author advocates a variety of different sizes of stays, stay blocks, and foundations, to meet different conditions, and this may lead to complication on the job. In the case of the majority of wood-pole lines a foreman is in direct charge in the field and, although an engineer is present at least part of every day, it is not always possible for him to inspect each individual operation and to superintend the fitting of each block or series of blocks. It might be cheaper to standardize and reduce the number of standard articles, even at the cost of a little expense in providing a greater factor of safety. Those cases where special construction is necessary can usually be examined on the site beforehand and prior instructions in regard to them may be given to the foreman.

I am not quite clear as to the method by which the sag Tables given in the paper are intended to be used. There seem to me to be two alternatives. Either one adopts for the particular type of line a certain average or maximum span length and deduces the sag for any other span length therefrom, or, on the other hand, one can read the sag for any span length required direct from the columns. For example, in the case of a line which has a 200-ft. and a 300-ft. span, should the sag reading be taken for each span as required, or should the average span be taken as being 250 and the sag be worked out for the whole line?

One of the author's slides showed a device for holding the conductor off the insulator of an angle pole while the chafer tape was being fitted. The problem I have come up against, particularly with the heavier size of copper and the longer span, is the difficulty of lifting the conductor out of the running sheaf, in which it has been run and sagged, on to the top groove of the insulator. It is very difficult to get more than three men on the pole-top to manipulate it, the lift is a heavy one, and the process is long and tedious. If a light and inexpensive tool could be devised for carrying out this operation it would eliminate a lot of trouble in the field.

* Paper by Mr. R. DEAN (see vol. 77, p. 749).

Some of the author's curves are rather complicated, and I think that in some cases a well-indexed tabulated system might be easier to follow than the graphs.

Mr. S. R. Siviour: The data relating to kicking blocks are most useful, but in their practical application to the varying types of strata, which are often unknown until the ground is opened, some latitude must be allowed. The standardization of kicking blocks is liable to lead to trouble unless due regard is paid to such special conditions as are found in this area, e.g. bog, peat, and running sand.

The author stresses his preference for stranded conductors, but I feel there is a case for the use of the solid conductor on low-voltage distribution up to 0·05 sq. in. This gives a slightly higher tensile strength, and good contact for tap connections. It has, however, only a limited use, because we seldom employ conductors of less than 0·10 sq. in. except for switch wires or sub-distributors in small villages.

The author deals with wood poles only, whereas fabricated-steel poles are comparable for the more important lines in rural work, and very satisfactory foundations for them can be provided with concrete.

As regards the typical designs shown in Fig. 6, (a) is the best as it avoids bird trouble and non-synchronous swinging. In my opinion (b) and (f) are poor, involving as they do a bird guard, which is an unnecessary and perishable fitting. Designs (c), (d), and (e), follow modern practice in the form of an anti-bird perch, which we may claim to have originated in this area.

With regard to the fuses shown in Fig. 12, I do not agree as to the necessity for these, as my experience does not accord with that of the author in regard to trouble with the insulated leading-in cable. Fuses in such a position are inaccessible without the use of a ladder.

Turning to Figs. 13 and 14, whilst I agree with the author's remarks as to unsightly V.I.R. connections between the transformer and the l.t. control box, I suggest that the arrangement shown is most unsatisfactory. It is practically inaccessible (unless the whole equipment is made " dead ") and therefore dangerous, particularly in bad weather, when most of the trouble on such equipment occurs. I feel that the correct position for l.t. control cabinets is at or near the foot of the pole, and it is quite possible to provide a neat arrangement for the l.t. connections thereto.

Mr. E. M. Pearson: The derrick pole described on page 791 would only be useful for the erection of terminal poles, and in view of the fact that such poles are few in number it would be uneconomical to transport this derrick pole from site to site. I should think that the extra cost for transportation would be more than that involved in calling the gang together to assist in erecting the terminal pole.

I do not like the layout of the author's transformer pole. I always insist upon l.t. fuse-boxes being placed below the e.h.t. connections, as it is dangerous for a man to climb a pole to replace a fuse when he has some live e.h.t. connections below him. I prefer the e.h.t. connections to the transformer to be as short as possible, and the l.t. fuse-box to be placed below the transformer, or even on the transformer tank. The author rather over-emphasizes the unsightliness of V.I.R. cables. He introduces another element of danger in that he advocates taking the bare line conductors through bushing insulators and into a metalclad fuse-box. The result is a number of bare live wires in a very confined space and close to earth. Further, it is very rarely that more than two circuits are needed from a terminal pole. In the villages I have to deal with it is only necessary to take one circuit away.

On none of the designs shown by the author is there any provision for protection against lightning. I think we should all like to be able to avoid lightning troubles, but unfortunately we cannot do so entirely. My experience, however, after 2 or 3 years of connection to the C.E.B. lines, has almost convinced me that the Board's method of running an overhead earth wire is as near perfection as we are likely to get. I used to be extremely nervous during a thunderstorm, fearing that our C.E.B. lines would trip out. We have had many thunderstorms since then, but on no occasion have we had any failure. On the other hand, our own rural lines, without an aerial earth-wire, trip out whenever a thunderstorm occurs in the vicinity. It would appear, then, that for reliability and protection against lightning an aerial earth-wire should be run; the additional first cost thus incurred may easily be offset by the greater reliability.

Mr. R. M. Longman: Detailed examination of Table 7 enables designs with different span lengths, sizes, and materials, to be rapidly compared. The author omits to mention one force, namely that of animals rubbing against a stay to a wooden pole. I should like to refer to a series of unexplained outages of an 11-kV line which were eventually traced to a cow rubbing against a stay wire for a pole from which a small tee-off was taken. This had gradually loosened the pole and, as the cow rubbed, the lines were flicked up and down, causing short-circuits. At last the cow was caught in the act.

I am interested to know whether the author has had much experience with segmental conductors, which have several advantages. Reference has been made to the effect of vibration, particularly on copper-clad steel and copperweld conductors. Has the author any information regarding vibration troubles on steel-cored aluminium conductors, and the maximum tension which may be utilized with safety?

Mr. A. Kelso: I agree with the author that the factor of safety of the pole foundation should be less than that of the pole. It is far safer to have a pole displaced than broken. On page 789 the author mentions that the cost of wayleaves may be capitalized at £1 10s. per pole; I should like to know what he pays for wayleaves in his own particular district. The prices of copper conductors given on the same page are now out of date, as the price of copper has recently risen considerably.

Referring to the last part of Part 1, at first sight it appears unbelievable that medium-length spans—of 400 to 600 ft.—are safer than others. One can see how this can be electrically, but not mechanically.

I agree with the author that low-voltage services should be fused. I would go as far as to fuse them on the pole, and so prevent service faults from affecting the main. Mr. Siviour is of the opposite opinion, but

perhaps he does not meet with the difficulty of obtaining admittance to the premises of some consumers in order to disconnect the supply when they have not paid their accounts. Disconnections can readily be carried out, however, if service fuses are mounted on the poles.

Turning to the important question of earth resistance, we have found a tremendous range of earth resistance with earth plates throughout an overhead line. I think this question has a direct relationship to lightning troubles. In my area of supply we have many lightning storms and our lines trip out quite often. We find that where we have good earths in boggy ground, lightning trouble is far less serious than where we go through rocky ground and have relatively high-resistance earths. I am afraid some engineers do not like to test earth plates. Has the author any experience of earth resistance on lines, and does he associate good earths with immunity from lightning trouble?

Dr. E. C. Walton: I should like to refer to the use of all-steel conductors for distribution, and to point out that the resistance of steel conductors with alternating current is higher than with direct current. Further, the reactance with steel conductors is considerably higher than with those of copper. For the sizes of steel conductors quoted in the paper the reactance is roughly 6 to 10 times that of all-copper conductors of the same size.

Mr. J. N. R. Perks: Regarding the house-service fuse bracket which the author recommends should be installed outside each house, does he also advocate the installation of the usual fuse cut-out inside the house? If so, it must add to the cost of the service, which it is so important to reduce in rural areas. If not, then I can foresee the trouble Mr. Siviour mentioned, namely, that of replacing fuses at night and in bad weather. Everyone nowadays is an amateur electrician willing to renew the house fuse, and consequently the risk of blowing the service fuse is greatly increased. The author's remarks about the behaviour of clay are most interesting. Does he consider that the loading of distribution lines is sufficiently intermittent to allow of the vagaries of clay being ignored?

On page 750 the author mentions that the methods used and devices installed to reduce fuel costs have only resulted in a very small reduction in the cost of energy at the station busbars, and rather implies that supply engineers would have been better employed in giving attention to the problems of distribution rather than to generation. It seems to me that the use of all the curves and tables included in the paper can only effect a saving of, say, 1 or 2 per cent in the cost of distribution, a percentage the author rather scoffs at in the case of generation. It is important to remember, however, that the small savings in the cost of generation which have been going on for many years past now enable the supply industry to compete for the enormous potential loads in the heating field. Ten years ago this was impossible, owing to the then high cost of generation. In the case of distribution we require not a reduction of a few per cent but one of 50 per cent if we are to deal adequately with the rural areas. The author gives data for usual and standard designs conforming to existing regulations. Has he given consideration to any radical

departure from these designs or to any modification of existing regulations which would tend toward a substantial reduction in the cost of distribution?

Mr. C. H. Bennett: I should like to know why it is necessary to go to the expense of fastening the kicking-blocks to the poles, and whether the author considers it really necessary to clip the kicking-blocks. We have found there is no advantage to be gained by attaching the kicking-blocks to the poles, if these are well set when first installed. If the kicking-blocks are not attached, the cost of the ironwork is saved and the boring of the timber avoided.

Mention has been made of the difficulty encountered where the poles are planted in clayey soil. When putting a line of poles right after it has heeled over, would not the author find it much better to pull each pole upright, leaving the block where it has been pushed, and to insert another block against the side of the pole, so avoiding disturbing the soil which has been consolidated under compression?

Mr. H. J. Fraser (*communicated*): It is obvious that, if the present rate of development is to be accelerated, rural distribution lines must be cheapened considerably, but I do not agree with the view that this should be done at the expense of reliability. Some attempt at standardization of the various types of h.t. and e.h.t. lines at present in use would be a step in the right direction. Porcelain insulators and steel brackets form a fairly high percentage of the total cost of a completely equipped overhead line; unfortunately, there are some hundreds of designs available for both these items, and whilst this state of affairs exists the cost is bound to be unnecessarily high. I suggest that for wood-pole lines intended for operation at 11 kV and 33 kV it should be possible to evolve, say, six standard designs which would cover all normal rural-distribution requirements in this country.

The Transmission Section of the Institution could perhaps set up a sub-committee which would invite the co-operation of the various undertakers. Existing designs could be submitted, with useful comments based on present operating experience. In this way standard designs could be evolved which would incorporate useful and proved features of designs at present in use. If a sufficient number of undertakers adopted the standard designs recommended by the sub-committee, manufacturing costs would be considerably reduced, with resultant savings on the overall cost of rural distribution lines and at the same time maintaining reliability.

The arrangement of brackets shown in Fig. 6 is open to some criticism. Practice has proved that bird guards are an unnecessary expense and complication. Given correctly-designed steelwork they should not be necessary. The design shown in Fig. 6(a) most nearly conforms to my idea of the basis for a good standard design, dispensing as it does with the necessity for bird guards. Precautions have also been taken against possible conductor clashing by adopting the tilted-triangle formation, and by placing the top conductor well above the pole top some economy in pole height is effected.

In the design of Fig. 6(f), the pole height could be reduced and bird guards dispensed with by taking both conductors above the pole top (one on each side). The

steelwork would of course have to be modified to suit this arrangement, but the resultant design would not be more expensive than that indicated.

I have no criticism to offer regarding the general design of the pole tops shown in Figs. 8(a) and 8(b), but I would suggest that in these days when so much opposition is raised to the erection of l.t. overhead lines every effort should be made to improve their appearance. In my opinion the addition of a wood or spun-metal finial to the pole top definitely improves the appearance, and it may be provided at a very small extra cost.

Mr. R. Dean (*in reply*): In reply to Mr. Pilling I can only reiterate that, for normal construction in average country, wood-pole lines have proved to be from 10 to 15 per cent cheaper than either steel or concrete construction. I agree that for spans of 600 ft. or upwards the case for the steel pole becomes more favourable, but in average undulating country this length of span is not often practicable.

The details of different sizes of stay blocks, foundations, etc., were included in the paper to show the varying effect with size, but it was not intended that all the different sizes should be carried as normal stock. Only one or two sizes of stay wire or block would normally be used, and in all cases where stay details are involved an ample margin can generally be allowed, with very little additional cost. It is, however, necessary and helpful to know fairly precisely what values are involved, so that one can readily ascertain the effect of any slight modifications.

In connection with the method of using the sag tables, it is generally recognized that when a conductor is being erected over a number of spans, the longest span in the particular section between straining-off poles determines the maximum tension to be applied in that particular section. Thus, in the case referred to, where a 200-ft. and a 300-ft. span are involved, the sag and tension would be obtained from the figures given in the tables for the 300-ft. span at the temperature applicable at the time of erection, and the sag would be checked off on the job by sighting a line across two sighting boards, one on each pole at the ends of the 300-ft. span.

With regard to the provision of a light and inexpensive tool for facilitating the running-out of conductors, there is now on the market a small metal-roller fitting arranged to be clamped to cross-arms, etc., by means of a butterfly-headed set-pin, and a special clip for temporarily clamping such a fitting to the top of an insulator should not be difficult to devise.

In reply to Mr. Siviour, the fuses referred to are normally fixed in an easily accessible position on the consumer's premises, but where this is impracticable they can readily be fixed on the nearest pole. I agree that the low-tension control cabinet is better fixed about 10 ft. above ground, so as to be well clear of all high-tension connections.

Replying to Mr. Pearson, the derrick pole described on page 791 is approximately 26 ft. long and 7 in. in diameter at 5 ft. from the butt, and in practice it has proved easy to transport and a great labour-saver, in addition to providing a far safer method of erecting heavy H-type poles. I have already referred to the position of the control box in reply to Mr. Siviour.

I agree with Mr. Pearson that a continuous earth wire erected immediately above the line conductors is probably one of the most effective safeguards against lightning and has the added advantage of ensuring a good earth in districts where a satisfactory earth may be difficult to obtain at an individual pole. The use of this additional conductor materially increases the height and strength of the poles required, and consequently the capital cost, and for this reason it is not often used on the less-important lines.

For the protection of the low-tension lines I advocate the use of condensers between each phase and earth, or of a lightning arrestor in the form of a small adjustable sphere-gap with a protecting fuse and blow-out coil.

I agree with Mr. Longman that segmental conductors have many advantages, including less wind resistance, less tendency to collect snow, easier handling in the field, and better protection from oxidation, particularly of the inner conductor, etc.; the extra cost of the segmental conductor has, however, prevented its extensive use, although, as indicated in Table 8A, it proves more economical in certain sizes than normal, round, stranded conductor.

Vibration troubles are almost sure to arise on steel-cored aluminium conductors where the latter have been erected with a tension to provide a factor of safety of 2 under worst conditions. Many miles of grid lines have since erection been equipped with vibration dampers to overcome this trouble, but I understand that, on new construction work, reducing the tension on the conductor to provide a factor of safety of $2\frac{1}{2}$ under worst conditions has proved quite effective in many cases.

In reply to Mr. Kelso, the annual payment for poles varies according to the particular class of land involved, from 1s. in grass land to 2s. in arable land, so that the capitalized value of 30s. is fairly representative.

With regard to spans of 400 to 600 ft. being safer than very short spans for high-tension lines, this is borne out by maintenance records for many miles of lines, both in this country and abroad. It is well recognized that every point of support is a potential source of weakness both electrically and mechanically. Further, with short-span construction, variations in length between adjacent spans are usually a much greater percentage than in the case of medium span lengths, and the variations of tension with temperature are thus far greater in short-span construction. Thus, where spans of uneven length occur when using short spans, considerable stresses can be thrown on the binders at intermediate poles owing to temperature variations only.

If Tables 7A to 7H are examined it will be seen, particularly with the smaller conductors, that unless ice has collected on them the tension on the conductors is very much below half the breaking strain, the difference being more marked the longer the span. With very short spans and fairly large conductors the variation in tension with temperature is very small, and, unless great care is exercised, the maximum allowable tension of half the breaking strain can very easily be exceeded at times of low temperature.

The earth resistance varies considerably in different localities (see details given in the paper by Mr. Ross, vol. 77, page 808) and it is generally recognized that

where springs exist, or there is boggy land, such ground is especially subject to lightning strokes. Where an overhead earth wire is used as a screen and is connected to ground providing a really good earth, the screening action is much more effective.

In reply to Mr. Perks, only one set of house-service fuses is advocated, and these should be fixed on the consumer's property in such a position that they can readily be reached by means of a light operating pole fitted with a spring device which grips the detachable fuse-carrier, this latter fitting into the porcelain housing by a movement similar to that necessary with a standard bayonet lampholder. Where no easily accessible position is available on the building, the service fuse can readily be fixed on the nearest pole.

Clay as a foundation is very treacherous, and, although one need not be quite so conservative in regard to transverse loads on pole foundations if of an intermittent nature, it is necessary to be particularly cautious and allow an ample margin when dealing with permanently-sustained loads such as occur on stay blocks, or on angle and terminal towers consisting of multi-member poles.

I regret that Mr. Perks has unfortunately misunderstood my reference on page 750 to the elaborate methods and organized efforts which have been made for years to reduce the costs of generation by even a small percentage. Every credit is due to those responsible for the splendid results which have already been achieved. What I intended to infer was that if our generating engineers, by their organized efforts and the keenness produced by tabulated results of works costs, can make such efforts to ensure a saving of even an additional 1 per cent, how much greater encouragement should our distribution engineers have in effecting savings in a field which now offers far greater scope for economies and in which, up to date, very few tabulated costs have been publicly recorded.

Mr. Perks's query as to methods of reducing costs of distribution is one which covers a very wide field and one which cannot be adequately dealt with in a discussion such as this. With regard, however, to methods of reducing costs of distribution by means of overhead lines in urban and rural areas, I would briefly mention the following:—

(1) Procedure for obtaining wayleaves and consents to schemes should be simplified. Where a type of construction has already been approved it should be possible for a supply authority to proceed under a general consent covering a specified area.

(2) I consider that the present Regulations for Overhead Lines El.C.53 prescribed by the Electricity Commissioners are very reasonable, with the possible exception of the stipulation that the factor of safety of single-pole foundations should be such that no movement takes place under worst conditions. This matter I have already referred to in my reply to the discussion in London (vol. 77, page 822).

(3) I feel that small supplies to very scattered properties in rural areas, which at present are a most difficult economic problem, will eventually be provided at extra high voltage by a single-wire construction with earth return.

I heartily agree with Mr. Fraser that it is highly desirable and should now be practicable to standardize a limited number of designs which should cover all normal rural-distribution requirements for this country, and such a course could not fail to effect considerable economies. I cannot agree that the tilted-triangle formation prevents clashing of conductors.

I thank Mr. Fraser for his reference to the desirability of fitting pole finials at the top of low-tension distribution poles, and I certainly agree that the small extra cost involved is well warranted, particularly where poles are erected alongside roads or prominently in view of the public.

Replying to Mr. Bennett, the reason I recommend clamping the kicking-blocks to poles is to ensure that the blocks can deal with both tensile and compression loadings, both of which are likely to arise, particularly in the case of straight-line poles.

Where this method is adopted the kicking-block must resume its initial position when a leaning pole is pulled back to an upright position.

DISCUSSION ON
"A REVIEW OF RECENT DEVELOPMENTS IN RURAL ELECTRIFICATION"*

SCOTTISH CENTRE, AT EDINBURGH, 10TH DECEMBER, 1935

Prof. F. G. Baily: The simplification and reduction in the cost of constructional design for rural distribution which this paper shows to have taken place in the past quarter of a century, is remarkable. In the past I have known it to be cheaper to put down an oil-engine set and battery than to take a supply from an overhead line a mile or so distant. The whole layout of overhead distribution is now less obtrusive, thus meeting the objection (in some instances not unreasonable) of injury to the amenities of the countryside. From this point of view the decision between wooden and lattice-steel poles is not easy. Wooden poles look rather less incongruous in the landscape, while, on the other hand, lattice poles are less visible at a distance, and the longer span that they permit reduces their number. Perhaps in wooded country the wooden poles will be preferred, but over open moorland and hill, where views are more extensive, the lattice pole has the advantage.

The problem of procuring a good earth connection is particularly difficult in Scotland, for there is little agricultural land and the subsoil is often volcanic or plutonic rock, covered with only a thin layer of earth which dries quickly. As the addition of mineral salts appears from the author's tests to be beneficial, it may be worth while to note that whereas sodium salts are rapidly washed out of the soil, potassium salts remain in the humus for a long time. It may be useful to try magnesium chloride, for it is very hygroscopic and will help to retain the water. As the soil contains carbonates and sulphates, there is sure to be interchange, and the carbonate of magnesium is rather insoluble. On this account calcium chloride, while no less hygroscopic, will be more readily precipitated, as both carbonate and sulphate are insoluble. An admixture of leaf mould or any vegetable refuse in the soil round the electrode will be beneficial in retaining moisture, and the effects should last for 3 or 4 years. The neighbourhood of shallow-rooting trees, such as poplars of all kinds, must be avoided, as they dry up the soil for many yards around.

Mr. J. Gogan: I have had a number of years' experience with rural distribution, and I would say that during that time it has been found that the greatest difficulty has been the question of amenities, not only in the more populated districts but also in the remote villages. I should like to know what difficulties the author's undertaking has experienced regarding amenities. I know that certain county councils which are not the authorized undertakers offer objection to the

erection of overhead lines; but the author's undertaking is operated by a county council, and I should like to know whether it meets with opposition from the residents or ratepayers, and how it gets over the difficulty.

The author refers to the use of single-phase supply; except for very light loads, single-phase distribution is in my opinion not the best practice.

Regarding the use of 5-kVA single-phase transformers, I consider that very little allowance is made for future development with such a small unit, seeing that if a cooker and a few fires are installed in one house the transformer will be overloaded. Apart from this the cost per kVA is exceptionally high in comparison with that of transformers of a larger size.

I notice that the author makes no arrangement for the protection of lines against lightning discharge. I should be glad to learn whether it is his experience that when lightning storms occur their effects are confined to certain sections of the area of supply.

Mr. P. Butler: The important point about the Dumfries scheme in which the author is interested is whether it is an economical proposition. In view of recent and probable developments, it is most important to have this fact clear. I am particularly struck by the simplicity of the scheme. It is a refreshing change from other systems which seem to be overburdened with capital costs, largely owing to their complicated design.

An important point dealt with in the paper is that of insulators, particularly those fitted on transformers. The present tendency seems to be to increase the flash-over value of the transformer insulators; in some cases we are asked to fit 33-kV insulators on 11-kV transformers. It will be appreciated that such a tendency must be used with great discretion, to avoid overstressing the transformer itself at the expense of the insulators. Where transformers are fitted with these large insulators, they must be designed for the same conditions; otherwise, in the case of a lightning stress, the weakest point is the transformer insulation rather than the insulators.

Mr. Ross advocates standardization, and then in Table 6 he gives details for a standard transformer and also for a non-standard transformer with special losses. To take the Edinburgh district as an example: the standard low-tension supply voltage is 400, and the transformers for the various local supply authorities are designed with no-load voltages varying from 400 to 424. Again, each authority has its own ideas as to the type of insulator and flashover value required, whilst one of them thinks that certain fitments on the

transformers are essential. Consequently, whilst there is a lot of talk about standardization it is very difficult to put it into practice.

From the paper it would appear that in Dumfries the low-tension voltage on the transformers is 415, whilst the declared voltage is 400. This is sound practice, since it enables the transformer tappings to be used for their correct purpose, i.e. to allow for variation in high-tension voltage. By this means the induction in the core is kept fairly constant, and thus the no-load losses are reduced.

In a certain number of cases the author advocates the use of steel wires; some supply authorities seem to be of the opinion that steel wires affect the line conditions in that they reduce the possibility of lightning disturbances. It would be interesting to know whether the author has any information in this connection.

Dealing now with the capitalization of losses, I have found that the figures given in the paper agree closely with those obtainable by using the Overhead Lines Association's Specification. The difference lies in making allowance for the regulation of transformers, but this is covered to a certain extent in the O.L.A. Specification by the fact that the regulation is specified at very low limits. Even if this point is taken into consideration, however, the 5-kVA transformer is seen to be a better proposition than the 1·5-kVA unit when one takes into account the allowance for development.

The author mentions that, in the kiosks he is using, he does not fit an l.t. circuit breaker; it would be interesting to know what the operating experience has been with the type of gear used.

Mr. J. Miller: In view of the importance of continuity of supply, I am surprised to find that the author dismisses in a few words the question of lightning troubles. It may be, of course, that in his area there is little trouble with lightning, but certainly other areas in Scotland suffered very severely last year. Unless some provision is made to minimize such troubles, continuity of supply cannot be hoped for. It would be interesting to know whether consideration has been given to this point, in the Dumfriesshire scheme.

Mr. D. H. Braid: I should like to mention some of the advantages of a form of lattice mild-steel pole of which we have used a considerable number. Owing to decay we have had to renew at least three wood poles on a main line within a period of 7 years, and I question whether any galvanized-steel pole will require to be renewed in such a short period. The steel pole of the type referred to is very easily climbed by engineers, etc., for the purpose of making repairs. On the other hand, when ordinary wood poles are employed, if anything goes wrong one generally has to wait until a lineman comes out to effect repairs, perhaps a distance of 20 miles. Although the steel pole may be of slightly higher first cost for smaller sizes, in the larger sizes it is definitely cheaper, and a single steel pole may replace composite wood poles; which, of course, eases matters such as wayleaves.

With regard to wayleaves, the author mentions that with steel-cored aluminium conductors one can get spans of 400–500 ft., but I would point out that with steel poles still longer spans are possible. Further, these steel poles are almost invisible beyond a distance of 200 yards, except in a bright light.

I notice that the author includes an incidental cost of £62 per mile for 0·05-sq. in. equivalent steel-cored aluminium; do his cost figures for the 0·05-sq. in. cadmium copper and ordinary hard-drawn copper also include that £62?

I should like to know whether the author has ever experienced difficulty with electrolysis on steel-cored aluminium lines. Some difficulty might be anticipated due to teeing-on a different kind of conductor. Special connectors are obtainable, but these are very expensive.

He mentions £25 per mile as the cost of erecting an aerial earth-wire. Does this figure refer to a new line, and does it include the cost of the extra height of the pole, ironwork, etc., required? In connection with spur lines the author refers to the omission of kicking-blocks. Is this practice justified, in view of the fact that, after the recent gale, even poles equipped with kicking-blocks were found to have gone over a little?

The author favours the development of ring mains, and he is in the habit of running these open. I should like to know what precautions are taken to ensure that the other side of the ring can be brought into operation in the event of a fault.

Regarding transformers, the 15-kVA Regulation of the Commissioners bears very hard on rural distribution. I can give an instance of one village with 50 small consumers and one 15-h.p. motor where a 3-phase supply is highly desirable. It seems to be high time this Regulation was modified. Has the author experienced any difficulty due to oil siphoning from transformers fitted with inverted-type insulators?

Earthing has always been a sore trouble in connection with distribution in rural areas, where the water-supply system is not so wide in its scope as in the city. It seems that the earth-leakage relay is going to solve a great many of our problems, and I should like to see this device made compulsory in all installations. Its use, even with an earth wire, would be beneficial in the long run. Earth-leakage relays should, however, be "voltage-operated" at, say, 50 volts. In this connection I would point out that, with earth-leakage protection installed on the main breaker, it seems possible for a consumer's earth-fault to trip out the whole of the l.t. distribution system.

May I remark in conclusion that if time-limit fuses can be made as reliable as the author indicates, some of us have been on quite the wrong track for many years in the matter of protective gear.

Mr. C. C. Murray: I notice that the author is an advocate of steel kiosks for substations. Has he ever employed brick kiosks? I have found that these can be installed very much more economically than steel kiosks, and also that they are very easy to design to the shape required to suit local conditions.

I agree with the author up to a point about fuses, but am afraid that the main reason for their use in rural substations is their relatively low cost.

He mentions the minimum size of transformers as 5 kVA. There are one or two instances, such as water-supply schemes, where the motor required is only of about ¾ h.p., and this is about all that is ever likely

to be required. To install a 5-kVA transformer for a ¾-h.p. motor is rather extravagant from the point of view of both cost and losses. Regarding reducing the iron losses of transformers, I am afraid the author has not taken sufficiently into consideration the question of regulation in rural distribution. Owing to the great length of the services, I have found it quite a difficult problem to keep within the required limits.

On page 805 it is stated that in rural areas there are few motors used of sizes greater than 5 h.p. It will be found, however, that it is not 5 h.p. but 15 h.p. which is generally required, and this is rather beyond the limits of the single-phase motor, a fact which wipes out the advantages of single-phase distribution to farms where electric power is required. We have only attempted to supply one village single-phase, and before the supply was available a consumer there wanted to put in a 15-h.p. motor for threshing. We have found it necessary in most cases with single-phase work to make provision for 3-phase supply by putting up sufficiently high poles.

I should like to have the author's views on using medium-size poles in villages where overhead services are being taken off the poles. Where those poles, which give more than the required factor of safety of 3½ on the line, are used with long services (up to, say, 40 or 50 yards), I have found that, to make a service at all tidy, it is necessary to pull it up so tightly that the pole is pulled over at the head, and of course a bent pole looks untidy.

On our system, over a period of about 10 years, we have only once had serious trouble with lightning, and in this case a pole was shattered. The lightning only affected the parts of the pole where there was no metal about.

Regarding underground compared with overhead distribution, most comparisons of costs do not take all the factors into consideration. The maintenance costs of overhead distribution are very high compared with those of underground, and I am afraid that the figures taken for maintenance cost are never sufficient.

Mr. H. C. Babb: There is one main point on which I differ from the author, and that is in regard to earth wires. I advocate an earth wire on every line, and for preference this earth wire should be on top, above the power wires, because from experience we have proved that the existence of such a wire materially reduces trouble, especially that due to lightning. I also like to see surge absorbers installed, at least where main ring lines enter substations, and I prefer bar-type current transformers to the wound type.

We have developed several types of lines. Our rural " H " type, although not as cheap as the author's, has proved very satisfactory, especially where boggy country has had to be dealt with. The cost of providing and putting an earth wire on top of a line amounts to about £66 per mile.

I should like to ask the author whether he has had any trouble due to vibration on his lines. The general use of single-phase lines is open to much criticism. We have usually found that soon after we have put up a single-phase line someone has required a big load, and the line has had to be altered. At the same time

I think that 3-wire single-phase distribution where small villages are concerned is to be commended, for the reason that it allows of a cheap and easy change—by the provision of an extra wire—into a 3-phase 4-wire system.

With regard to low-tension services, the author's method of leading in the wires may be perfectly good, but I prefer the use of Maconite cable drawn into a galvanized tube. We have found this to stand up to service conditions very well, whereas other methods have failed in 5–6 years. On our system, wherever steel wire has been used on overhead lines near collieries and industrial works, after 7–8 years it has had to be replaced.

I do not approve the author's method of putting up transformers without fuses. We fuse every transformer we put up, and we find that in the event of lightning the transformer tends to discharge the lines; the fuses blow, but the transformer is not hurt, and no further damage occurs. In some cases we put in spill-over insulators in addition, in close proximity.

My impression is that before long we shall find that our rural distribution systems are too small. In the early days no one anticipated the domestic and industrial development that has occurred, and, with the application of electricity to the development of the land, it is impossible to say what loads may soon have to be catered for. In all probability, underground feeders will be laid to various points of the existing overhead systems; these would tend toward stability without taking away the advantages in costs which overhead distribution provides.

Mr. D. Ross (*in reply*): Replying to Mr. Gogan's question regarding difficulty encountered in connection with amenities, I wish to state that this difficulty has not arisen on the undertaking with which I am engaged. Having regard to the simplicity of design, choice of route, and selection of pole positions, no objections have been raised. It is necessary to mention, however, that the conditions in this case may be somewhat different from those obtaining in other parts of the country, particularly where the undertaking is operated by a company. In this case the undertaking is operated by a county council, and consequently the goodwill of the landowners, occupiers, and other ratepayers, is behind it.

Mr. Gogan doubts the advantages of single-phase distribution; I can only repeat the statement made in my paper that this system is sound not only technically but also economically. I have actual experience where the use of single-phase distribution has resulted in a saving of approximately 40 per cent on the capital expenditure. It must not be assumed, however, that this saving could be effected on the total cost of a complete rural distribution scheme, as the main distribution lines and large distribution networks will require to be of the 3-phase type.

Mr. Gogan raises the question of the use of 5-kVA single-phase transformers and considers that units of this size are too small to allow for developments. This is probably so where several consumers are concerned, but I should like to emphasize that a 5-kVA transformer is only used for one consumer and, considering the diversity obtaining on an installation, a 5-kVA unit is adequate to meet the demand of approximately 10–12 kW of connected load.

My experience of lightning disturbances indicates that,

although the majority of lightning storms affect the whole area of supply, there are frequently local thunderstorms where only one section of the distribution is affected, bearing in mind, of course, that the area of supply is approximately 1 000 square miles.

I am glad to note that Mr. Butler concurs with my views on the grading of insulators, particularly as to the increasing of the flashover values of transformer insulators. With regard to his question concerning the effect steel wires have on the line conditions during lightning disturbances, it is my opinion that the type of conductor used has little effect in minimizing trouble caused by lightning storms.

Mr. Butler mentions that he would like some further information regarding the operating experience of low-tension circuit breakers in kiosks, etc. In reply I would say that, for rural distribution, high-tension and low-tension fuses are quite satisfactory, discrimination being obtained when cartridge fuses are employed on both h.t. and l.t. sides. Discrimination is difficult to obtain where the rewirable open type of fuse is used on the l.t. side. Where damage to motors might be caused as a result of single-phasing due to one fuse blowing, it is perhaps advisable for a triple-pole automatic circuit breaker to be used.

Mr. Miller also raises an important question regarding lightning troubles; although I have referred to this only very briefly in my paper, I am fully aware of the trouble and damage caused by lightning. In my opinion, no effective cure is obtainable at a reasonable cost. For instance, on the system where I am at the moment engaged, a scheme was prepared for providing protection against lightning storms at an estimated cost of £10 000. After careful consideration of the annual value of damage caused, and the number and duration of interruptions, it was decided that the capital cost of complete protection could not be justified on a rural distribution scheme.

Mr. Braid's experience of the life of wood poles is unusual, as I have had approximately 20 years' experience of their use and the percentage of renewals during this period has been extremely small. For the majority of poles, properly seasoned and creosoted, a life of at least 30 years can be expected; in fact, the Post Office Engineering Department have experience of poles being in service from 40 to 50 years. Although I admit the advantages of lattice mild-steel masts, these only apply to relatively high-capacity transmission lines, and so far as rural distribution lines are concerned his contentions do not apply. Mr. Braid mentions that with steel masts and using steel-cored aluminium conductors spans greater than 400–500 ft. are possible. Surely the span length and type of support are governed by economic considerations and by the size and spacing of conductors. I am quite sure that, for rural distribution work with 0·05-sq. in. copper-equivalent steel-cored aluminium conductors, steel masts could not be economically employed. The figure of £62 given for incidental costs is for 0·05-sq. in. copper-equivalent steel-cored aluminium line, and the figures given for 0·05-sq. in. cadmium copper and hard-drawn copper do not include this sum.

I have had practically no experience with regard to electrolysis on steel-cored aluminium lines. This type of conductor should be erected with care, and where there is a tendency for strands to open out—such as at tension clamps—this part of the conductor should be treated with a special compound to prevent the ingress of water. At tee-off positions a heavily galvanized mild-steel parallel-groove clamp, which is very cheap, is all that is necessary. Although special bimetal connectors are obtainable, it is agreed that these are expensive and are not always reliable. The figure of £25 per mile referred to as the cost of erecting an earth wire does not include allowances for extra diameter or height of pole, but only includes conductor, conductor fittings, and erection.

The practice of omitting kicking-blocks is only permissible on the lighter lines with two conductors; but this again is a matter of design, depending on the span length, size, and number of conductors employed. Mr. Braid states that even poles equipped with kicking blocks have been found to go over. This frequently occurs on a newly erected line, particularly if a storm takes place before the ground has had the opportunity of consolidating, and as there is a greater area of ground disturbed on poles with kicking blocks than on those without, the possibilities of such poles going over prior to consolidation are obviously increased. It is my experience that after 12 months poles very seldom go over.

With regard to the possibility of oil siphoning from transformers fitted with inverted-type insulators, provided a suitable terminal is used there is no reason to fear this. The disadvantage of this type of terminal is that the oil cannot be brought to the top of the transformer tank, thereby covering all connections; whereas with the upright type of terminal this disadvantage is overcome and the possibilities of flashovers on the top of the tank are eliminated.

Mr. Braid's query concerning the possibility of a consumer's earth fault tripping out the main switch fitted with earth-leakage protection does not arise, as the earth-leakage trip circuit on the main control switch is in parallel with the main neutral earth-connection. Consequently only a proportion of the earth-leakage current passes via the earth-leakage coil, the actual value of which will depend upon the resistance of the two circuits; and as the earth circuit-breakers on the consumers' premises will be operated by the total leakage current, they will be more sensitive and will operate before the main control switch.

Mr. Murray mentions that brick kiosks can be installed much more economically than steel kiosks; I am rather doubtful about this, as steel doors are generally required on three sides of a brick kiosk. Incidentally, brick kiosks suffer from the disadvantage that they are permanent structures and cannot be as readily moved to a new position should the necessity arise.

As Mr. Murray considers that in some instances the installation of a 5-kVA transformer is extravagant, his views appear to be opposite to those of Mr. Gogan, and I can only repeat my previous statement that for both technical and economical reasons transformers smaller than 5 kVA which will operate on 11 000-volt supply should not be used. Moreover, the case given is exceptional and should not be allowed to influence the standardization of sizes and design. Generally speaking, where motors of this size are required for pumping they

are adjacent to premises which are or should be receiving the electricity supply for other purposes.

Contrary to Mr. Murray's assumption, the question of regulation has received careful attention. So far as the smaller sizes of transformers, located adjacent to consumers' premises, are concerned, low core loss is of more importance than regulation, as the load factor of such transformers is relatively small; and, moreover, on a rural scheme the number of these small transformers is a considerable proportion of the total number of transformers installed, the ratio being approximately 10 : 1. With regard to the larger units, of 25 kVA and above, regulation or low copper loss is certainly of more importance than core loss.

I cannot agree with Mr. Murray's assertion that it is generally a 15-h.p. motor which is required for farm work. It is admitted that occasionally a 15-h.p. motor is required for threshing, but this can readily be dealt with by a single-phase supply. My experience of providing supplies to several hundred villages and farms by means of single-phase distribution shows this to be definitely the most economical system. The revenue to be obtained from a 15-h.p. motor driving a thresher, which would only be run approximately 2 hours per week, could not possibly justify the additional capital expenditure which a 3-phase supply would involve.

I see no reason why minimum-size poles should not be used for distribution in villages, even where overhead services are taken off without the poles being pulled over. Obviously, care must be taken to ensure that the service is not pulled up to the maximum permissible tension. Generally a factor of safety of between 3 and 4 is allowed. Occasionally, with a particularly long service where the conductors must be pulled up to the maximum tension, special attention must be given to the staying of the pole or the insertion of a kicking block.

I am pleased to learn of Mr. Babb's experience with reference to the erection of an earth wire above the power conductors, and that he considers that this arrangement materially reduces trouble from lightning. Unfortunately this has not been the general experience, otherwise a more extensive use would have been made of this method. Moreover, the cost given of £66 per mile for erecting an aerial earth-wire would be out of the question for a rural distribution scheme consisting of, say, 600 miles of lines, as obviously the sum of £40 000 could be much better employed. Admittedly, surge absorbers installed between the overhead line and the equipment in substations give the necessary protection, but here, again, the question of cost arises. In the most important substations no doubt this expenditure can be justified, but for small rural substations it is doubtful whether the additional expense would be warranted.

I note that Mr. Babb prefers " H " type construction, but this is entirely a matter for the individual engineer to decide. So far as main transmission lines are concerned, this form of construction may have advantages, but, for rural distribution lines, single-pole construction cannot be improved upon.

In reply to Mr. Babb's question regarding trouble due to vibration on lines, I would inform him that no serious trouble has yet been experienced.

I quite agree that if steel conductor is used in the vicinity of industrial works its life will be considerably shorter than that given in the paper, but of course I do not advocate its use in these circumstances.

Whilst Mr. Babb may prefer to use galvanized tube for the lead-in cable, the problem of earthing arises. My experience of this method of distribution and service has proved that a galvanized tube is quite unnecessary. The type of service described in the paper has now been in use for well over 10 years and no failures have occurred.

I consider it unnecessary to fuse each transformer, except on a main line, and in this case the practice is adopted principally to ensure that a fault on the transformer will not affect the main line. Transformers on spur lines need not be further protected other than at the tee-off position.

DISCUSSION ON
"A CATHODE-RAY OSCILLOGRAPH FOR THE DIRECT MEASURE-
MENT OF HIGH-VOLTAGE TRANSIENTS "*

Mr. R. Davis (*communicated*): I should like to raise two points in connection with the paper. (1) Are the ordinate and abscissal axes mutually at right angles from one side of the record to the other in the case of the author's high-voltage deflecting system? The question is important when small time intervals, referred to two different ordinate positions, are measured. (2) Does the author propose to incorporate facilities for adjusting the sensitivity of the high-voltage deflecting plates under vacuum, or, alternatively, to prove the voltage divider and low-voltage deflecting plates incorporated in the system by comparative tests, using the high-voltage deflecting plates? The paper does not appear to give any results of the comparison of the two arrangements.

Dr. J. L. Miller and **Mr. J. E. L. Robinson** (*communicated*): To us, one of the most interesting points in the paper is the decision to adopt a method of controlled transient operation for laboratory testing-work. In the interest of accuracy, we ourselves have, wherever practicable, always made it a policy to arrange synchronization independently of the potentiometer circuit, thereby avoiding the use of a delay cable; and we have only adopted the latter where the nature of the work demanded it. Incidentally, in connection with delay cables, the author states in the Introduction that there is no practical means of ascertaining the magnitudes of the cable errors. This is rather surprising, in view of the fact that any oscillograph where the initiation of the transient is under control is suitable for their estimation.

It is also very noticeable that although the paper is purportedly concerned with an oscillograph for direct measurement of high voltages, a great deal of attention is devoted to a capacitance potentiometer. We wonder if this is an indication that the author has found the former to be somewhat restricted as regards its practical adaptability. All that the author says in favour of such an oscillograph is very pertinent, but the disadvantages of the rival condenser-potentiometer system are, in our opinion, unfairly described. Thus it is rather beside the point to dismiss capacitance dividers with the remark that, as usually constructed, their capacitance is not much less than 160 $\mu\mu$F. There is no reason why the condenser-type bushing construction should be adhered to, and in the cylindrical air-insulated arrangement which we have employed the capacitance is only a few micromicrofarads over the range of voltages considered. We have found this type very satisfactory and to respond accurately up to the highest equivalent frequencies to which ordinary investigations have given rise, although there has not yet been any occasion to examine, for example, wave fronts of less than 0·15 microsecond at high voltages.

* Paper by Mr. A. K. Nuttall (see page 229).

With regard to the potentiometer described by the author, it seems certainly a very neat idea to use the deflection-plate capacitance as the low-voltage element, but in actual practice the gain is slight, while the method has the disadvantage of requiring a high-voltage connector right up to the oscillograph. Actually, the active portion of the high-voltage capacitance of a properly designed and screened potentiometer is only a fraction of the total high-voltage electrode capacitance to earth. Consequently for a given potentiometer ratio any increase in the low-voltage element capacitance, entailed in separating the potentiometer from the oscillograph by a few feet of air-dielectric shielded flexible lead, causes very little increase in the total capacitance, and in practice, of course, it is very convenient to be able to afford this greater flexibility of the equipment, which is justifiable wherever the cable effect of the lead is sufficiently small for the nature of the work in hand.

Although admittedly still pursuing the same policy of absolute minimum overall capacitance of potentiometer, the method of adjusting the sensitivity from the high-voltage electrode seems just a little cumbersome. The method which we employ consists in using a fixed high-voltage system over a range of voltages while the sensitivity is controlled by loading capacitances in parallel with the low-voltage system.

The oscillograph itself is a notable contribution to oscillograph technique, and the numerous problems arising from such a design have all been solved in a very satisfactory and original manner. The use of cylindrical high-voltage deflection electrodes in conjunction with the earth screens is very ingenious, and in view of its linear calibration, which is demonstrated, the author is to be complimented upon it. It is, however, a slight disadvantage to have to withdraw one-half of the earth screen when a change-over from, for instance, inter-turn to voltage-to-earth measurements is being made.

A few other minor points also call for comment. One is the attention which is drawn to the necessity for extreme cleanliness in the assembly of the oscillograph, compared with the relatively haphazard handling which is possible with the normal instrument. We would therefore ask the author whether the degree of cleanliness required is such that routine operation is possible by those not too skilled in vacuum technique. A second point arises from the comments, not peculiar to the present paper alone, on the minor troubles associated with the use of photographic film. Drying and vapour troubles are negligible with plates, and one wonders why these are not more generally used. A third point refers to the method of viewing in the author's apparatus, and we would ask whether he attributes the comparatively

low visual sensitivity of 2 microseconds to the indirect viewing method.

With respect to the transient delay circuit which the author employs for synchronization, we note that a method of tripping is used involving the raising of the potential of an electrode. We have found that even less inconsistency is obtained by the action of a decreasing potential on the tripping sphere. We also were led to the use of a high-voltage tripping circuit because of the inconsistency of tripping by small impulses propagated from the oscillograph.

It is interesting to note the author's experiences in the use of collars supporting the deflection electrodes inside the vacuum. Several years ago when we had occasion to use deflection plates which operated at a mean potential of 60 kV to earth, although at that time, at an actual difference between plates of only a few kV, we too found it necessary to adopt the simple cantilever method of mounting.

The record of the author's conjectures on the source of the oscillations observed in the oscillograms is also very interesting, although the statement that the time-constant of the plate circuit is too small to influence faithful response seems hardly reconcilable with that of the necessity of the damping resistance being capable of withstanding instantaneously the full voltage across its length.

Mr. G. J. Scoles (*communicated*): An interesting problem in electron optics arose in connection with the oscillograph described in the paper. Early oscillograms showed that the recorded zero line was not truly vertical, although the timing plates lie horizontally. Investigation showed that this effect was due to the action of the stray magnetic field of the focusing coil upon the electron beam.

If reference is made to Fig. 1 it will be seen that the plane of the focusing coil is within a few inches of the timing plates, and there will be an appreciable magnetic field due to this coil in the region of the timing plates and for some distance beyond them. Due to the radial component of this field, the beam, after deflection by the timing plates, will suffer a lateral displacement, the direction of which is determined by the position of the beam relative to the axis of the coil, no displacement taking place when the beam coincides with the axis. The recorded zero line will thus be inclined from the true vertical. This stray field was reduced as much as possible by fitting iron pole-pieces inside the tube, but a slight inclination of the zero line still persisted.

This inclination was finally eliminated by the winding of a new coil round the oscillograph between the timing plates and the transient plates and as close to the former as possible, and by passing a current through it so that its field opposed that of the main focusing coil. The effect of this is to cancel, on the whole, the field causing the inclination of the zero line, to an extent dependent on the current flowing through the coil. On test it was found possible by this means to vary the inclination of the zero line through as much as 30° on either side of the vertical.

As the field strength required for this purpose is small compared with that of the focusing coil, it was not anticipated that the action of the latter would be appreciably affected by the compensating coil. This was found to be verified in practice.

An arrangement similar to the above, but for a somewhat different purpose, has been described by Stabenow.*

Mr. A. K. Nuttall (*in reply*): I am indebted to Mr. Scoles for his suggestions and assistance which led to the improvements described by him. The stray field of a focusing coil wound externally upon a tube of large diameter, as in the case of the present instrument, is, of necessity, strong and of wide extent, despite any measures which may be taken to concentrate the field in this region when it is required. Constructional features rendered the incorporation of an internal focusing coil very difficult, and the measures described by Mr. Scoles would appear to provide a satisfactory and unique solution of the problem of the oblique zero line.

In reply to Mr. Davis I would state that, since the addition of the modifications described by Mr. Scoles, the ordinate and abscissal axes are mutually at right angles over a range of abscissal deflections of approximately 1 in. on each side of the central axis. The nature of the high-voltage deflecting field is such as to produce a small degree of obliquity outside this range and, for accurate measurement of small time intervals by means of the high-voltage plates, it is necessary to delay the transient so that the record appears inside this zone.

No provision has yet been made for adjusting the sensitivity of the high-voltage plates under vacuum, although it is hoped to make this modification in the near future. Comparative records of the oscillatory conditions obtaining after the breakdown of a sphere gap have shown the responses of the capacitance divider and of the high-voltage plates to be identical at frequencies exceeding 5 megacycles. These records were of necessity taken at a voltage of the order of 100 kV, at which full-scale deflections were obtainable by means of the high-voltage plates. It is not anticipated, however, that the response of the divider will be materially altered when its capacitance is increased to produce full-scale deflection at lower voltages.

I should like to thank Dr. Miller and Mr. Robinson for their communication, which raises many interesting points, their remarks on the subject of potential division being of considerable importance. My observations on the capacitance potential-divider were not intended to condemn outright a device which is obviously of the greatest value in the recording of high-voltage transients, and I was in fact at the time of publication unaware of the characteristics of the potential divider which is employed by Dr. Miller in his laboratory and upon which he is to be congratulated.

In describing the capacitance potential-divider employed in conjunction with the instrument, I had not intended to give an impression of any limitation in the use of the high-voltage plates other than that mentioned in Section 3(c) of the paper. The high-voltage plates are in fact used on all occasions when the voltage to be recorded is such as to give a convenient deflection; in the laboratory where the present instrument is in operation a second high-speed oscillograph is available for use in conjunction with tests at voltages up to 1 million volts,

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thus releasing the high-voltage oscillograph for many important investigations involving voltages of 100 kV or less.

In connection with his remarks upon the relative unimportance of the capacitance of the air-dielectric shielded lead between the oscillograph and the potentiometer, one must bear in mind that if, as in Dr. Miller and Mr. Robinson's case, the potentiometer is constructed with a view to obtaining the minimum capacitance of the high-voltage electrode to earth, the capacitance of such a shielded lead may influence the design very considerably. For example, the capacitance of 10 ft. of such a lead having an inner conductor of diameter 0·032 in. and an outer conductor of 2 in. diameter will be of the order of $35 \, \mu\mu$F. If the oscillograph be designed to give a full-scale deflection at 500 volts, and it is required to produce this deflection in recording a minimum value of 5 kV applied to the potentiometer, it is evident that the capacitance of the active portion of the high-voltage arm must be of the order of $4 \, \mu\mu$F. As Dr. Miller and Mr. Robinson have pointed out, the total capacitance of the high-voltage electrode to earth must, for reasons of good shielding, be considerably greater than that to the active portion, and it would thus appear difficult to construct such a condenser having a capacitance of much less than $20 \, \mu\mu$F; as will be seen from the above, this figure is governed almost entirely by the capacitance of the shielded lead, which must therefore be designed with considerable care.

As stated in the paper, one of the considerations which led to the use of the variable high-voltage condenser was the evidence of recorded oscillations which occasionally arose from the placing of a low-voltage condenser in parallel with the low-voltage transient plates, and which occurred most frequently when it became necessary to record steep-fronted waves. The adjustment of the high-voltage capacitance is in fact not nearly as cumbersome as might appear, being effected by the simple expedient of turning a handwheel which raises or lowers the high-voltage electrode inside its shield. Since the potential divider is designed to operate at the relatively low voltage of 150 kV, no difficulty or danger is involved in bringing a high-voltage lead to it, in view of the fact that the divider terminal stands about 9 ft. above floor-level.

Tests made by means of the high-voltage plates to examine the response of the directly-connected capacitance potential-divider now lead me to agree with Dr. Miller and Mr. Robinson that the use of this latter together with the uncontrolled transient system provides an entirely adequate means of checking the response of the potential divider and delay cable. At the time of construction of the instrument it was considered desirable to develop a means of direct recording without the use of a potential divider of any kind. Comparative tests have also shown that the errors inherent in the delay cable are such as can be predicted by analysis.

The question regarding the cleanliness called for in the assembly of the instrument raises an interesting point. When the instrument was first used, some difficulty was experienced in avoiding glow discharge inside the tube when voltages of the order of 100 kV were applied to the deflection plates. Considerable improvement was effected by applying high-voltage direct current to the plates and thus "cleaning up" the portions of the tube within range of bombardment from the plates. It has been found that this difficulty has gradually disappeared with time and normal use, and quite early in the life of the tube a condition was reached in which 100 kV could be applied as a matter of routine; it is in fact now possible to apply voltages considerably in excess of this value. In view of the fact that in changing a film it is only necessary to handle the end plate and the camera box, which are both easily accessible for cleaning, no advanced knowledge of vacuum technique is required in the use of the instrument.

Whilst agreeing with Dr. Miller and Mr. Robinson that photographic film inherently contains more water vapour than plates, I would point out that the use of film considerably simplifies the mechanism of the camera; we find that the difficulties due to water vapour are more apparent than real if one adopts the very simple precaution of storing the films in a vacuum desiccator for a day or two before use.

The relatively low visual sensitivity quoted was based on the use of a cathode current of 0·5 mA, at which it is found that the cathode life is conveniently long. Considerably higher visual sensitivities are possible if the current be increased to 1 mA; the continued use of this current, however, shortens the cathode life. I agree that the use of the indirect viewing system is probably a contributory cause of the low visual sensitivity; considerations of the safety of the observer, however, rendered this imperative.

It has been found, since the publication of the paper, that the oscillations occurring in the oscillograms shown were due to causes other than that of the excitation of the natural response of the loop including the oscillograph tube and the deflection plates. I must, nevertheless, disagree with the opinion that my statements that the damping resistance must withstand momentarily the full applied voltage, and that the time-constant of the circuit is too small to affect faithful response, are incompatible. Fidelity of response is a relative term only, and Dr. Miller and Mr. Robinson apparently do not disagree with me in regarding a time-constant of 0·0072 as negligible; nevertheless, were it possible to apply to the instrument a wave having an infinitely steep front (i.e. the Heaviside "unit function") the whole of this voltage would initially, if only momentarily, appear across the resistance. Whilst such a wave never occurs in practice, the collapse of voltage across a sphere gap on sparkover approximates very closely to it, and it appeared necessary to design the resistances to withstand the most severe conditions possible.

A METHOD OF STABILIZING THE FREQUENCY OF A RADIO TRANSMITTER BY MEANS OF AN AUTOMATIC MONITOR*

By H. A. THOMAS, M.Sc., Associate Member.

(From the National Physical Laboratory.)

SUMMARY

The paper describes a means of automatically stabilizing the frequency of a simple self-oscillatory system such as is used in small radio transmitters. The frequency is controlled by a master oscillator of small power and a monitoring condenser which automatically corrects the frequency variations due to changes in circuit parameters. The degree of stabilization which can be obtained is dependent upon the rate of variation of the circuit parameters, being of the order of 10 parts in 1 million for slow changes and 30 parts in 1 million for changes at a rate of 25 times a second. Means of eliminating " key chirps " in the received signal are also discussed.

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(1) INTRODUCTION

The stability of the frequency of radio transmitters is a matter of great and increasing importance in the advancement of communication. In the case of transmitters working on a fixed carrier-frequency, a high degree of constancy can be secured by the amplification of the output of a master oscillator, the frequency of which is controlled by that of a tuning-fork or quartz crystal. Such methods, however, are not conveniently applicable to cases in which it is necessary to adjust the frequency to any value within a given band, or even to any one of a limited number of fixed frequencies in such a band, for in such cases the requisite adjustments and controls become numerous and complicated.

Transmitters of this kind are used in certain cases of aircraft, marine, and mobile land communication, where, in many instances, considerations of space, weight, and simplicity of operation, limit the apparatus to some form of self-oscillatory circuit in which the aerial is either directly coupled to the main oscillatory system or is coupled to it by a single tuned circuit. In all such cases considerable undesired variations of frequency are liable to occur, the chief causes of these being:—

(*a*) Changes in the electrical characteristics of the components of the oscillatory circuit due to variation of temperature of the components, arising either from changes in ambient temperature or from the dissipation of electrical energy as heat.

(*b*) Changes in the electrical characteristics of the aerial due to variations in insulator losses or to changes of configuration arising from climatic effects.

(*c*) Changes in the electrical conditions of maintenance of oscillation (e.g. variation of supply voltages).

It was shown in a previous paper† that by far the greater part of the observed variations of the frequency of self-oscillatory circuits is due to the first of these causes. Such frequency variations can be minimized by attention to detail in the design and disposition of the elements of the assembly, or even by thermostatic temperature control, but these methods, especially the latter, are more easily applied to systems of very low power, such as master oscillators, than to medium- and high-power transmitters.

The effects of the aerial parameters on frequency can also, in theory, be minimized by care in design, but in many cases the actual conditions of operation preclude the required rigidity of construction.

For the above reasons, therefore, there would appear to be some scope for a system of transmission in which the frequency is determined by that of a master oscillator and can be given any value in a desired range, but in which the complication involved in several stages of power amplification over a radio-frequency band is eliminated. The system known as automatic monitoring is of this character. A number of schemes of this type have already been described,‡ but it is thought that the method outlined in the present paper has some advantages of a practical nature.

(2) THE AUTOMATIC-MONITOR PRINCIPLE

In ordinary master-oscillator systems, the transmitting aerial is associated with the initial frequency-controlling or amplifying circuits, and the transmitted frequency is therefore identical with, or an integral multiple of, the frequency of the controlling oscillator. In automatic monitor systems, on the other hand, the master oscillator is used as a standard of reference, with which the transmitter frequency, or some harmonic of it, is compared. Any departure from some definite relationship between the frequencies of the transmission and of the master

† H. A. THOMAS: " The Stability of Inductance Coils for Radio Frequencies," *Journal I.E.E.*, 1935, vol. 77, p. 702.   ‡ See Section (2).

oscillator brings into play a mechanism which tends to annul this departure.

For example, in a system that has been operated at the S. Assise* radio station, the heterodyne response due to interaction between the transmitter and the master oscillator is amplified in a system having a fairly steep frequency characteristic; after rectification and further amplification, the direct-current response is passed through a winding on an iron core magnetically linked with the main inductance; this rectified current also operates an auxiliary tuning condenser by electro-magnetic action. In this manner, restoration of frequency to a specified value is obtained by variation of the inductance and capacitance of the oscillatory circuit. It appears that the system was subsequently abandoned in favour of crystal control, which suggests that the station in which it was tried was not of a type for which the flexibility of the automatic-monitor system is really required.

In another scheme† a mechanical controlling device is adopted, but the inertia of the moving system is rather too great for the correction of rapid frequency-changes.

The scheme is therefore put forward as an addition to the range of existing possibilities for consideration in cases where transmissions of medium power—i.e. up to a few kilowatts—are required in fixed or temporarily fixed stations, with a degree of flexibility in frequency that would make undesirable or impracticable the usual type of master-oscillator control.

(3) MODE OF OPERATION

The frequency of a controlling oscillator is adjusted with respect to that of the main transmitter so as to produce an audio-frequency beat note in a suitable circuit arrangement. This audio-frequency e.m.f. is amplified and passed to a selective network consisting of two circuits in parallel. The one circuit is inductive and the other capacitative, so that at some predetermined frequency the alternating current in each is the same. If the beat frequency increases, the current in the capacitative branch increases, while the current in the inductive branch decreases, and if the frequency decreases the action is similar but reversed. These audio-frequency currents are rectified in each branch separately and
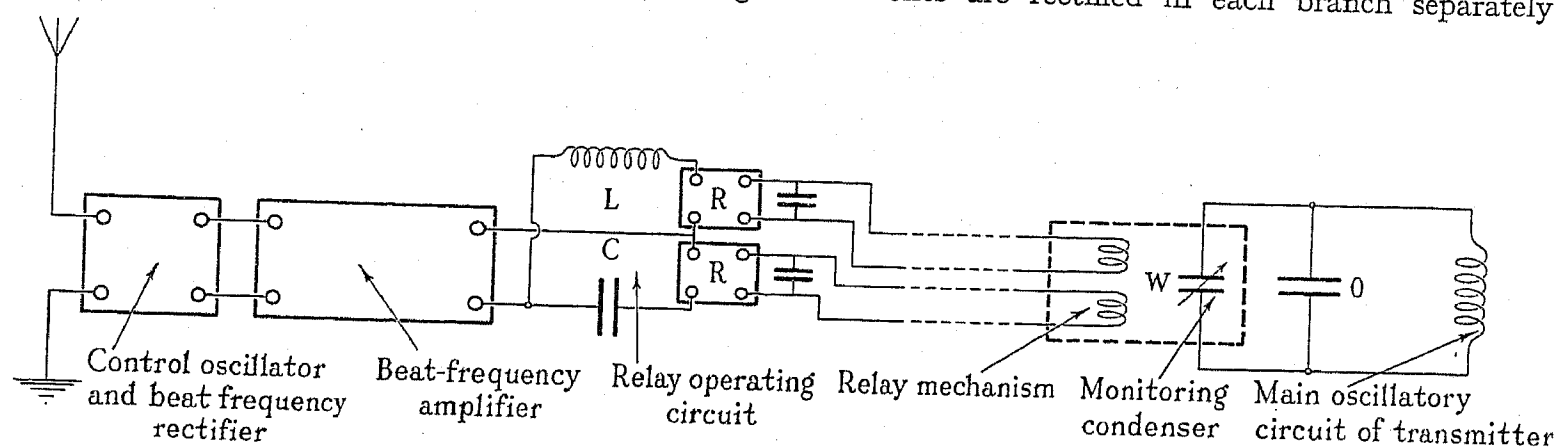
Fig. 1.—General circuit arrangement of automatic monitor.

The authors of the above scheme describe an alternative arrangement in which frequency control is obtained by changes in the reactance effect of a valve associated with the oscillatory circuit. This purely electrical device is satisfactorily free from inertia, but has the serious drawback that the correcting reactance reverts to its initial minimum value every time the oscillations are interrupted by keying. Moreover, in neither case is the mechanism absolutely independent of the amplitude of the oscillatory current, though it would be practically so in the first case.

In the system described in the present paper the inertia of the mechanism has been made sufficiently small to permit of the control even of comparatively rapid fluctuations of frequency. The operation of the device is also independent of the amplitude of the oscillatory current in the transmitter, a feature which, incidentally, permits of amplitude modulation of the transmission without loss of control. Furthermore, there is no restoring force on the mechanism which produces the required corrections of frequency, and therefore no reversion to an uncorrected condition on the part of the transmitter when the oscillation is interrupted.

passed to two windings on a differential relay which operates a small monitoring condenser connected in parallel with the main tuning condenser. The windings are so arranged that this condenser annuls the frequency variation of the main signal transmitter.

Fig. 1 illustrates the general circuit arrangement. An audio-frequency beat note is obtained by heterodyning the emitted signal by means of a control oscillator, and this e.m.f. is passed to a 3-stage amplifier. The output is taken to the two parallel-connected circuits containing the inductance L and condenser C respectively, and the alternating current is rectified by the two full-wave copper-oxide rectifiers R, the d.c. circuits of which are shunted by condensers of large capacitance to eliminate the alternating component. The current delivered by these rectifiers is taken to the relay windings W, which operate the monitoring condenser connected in parallel with the main oscillatory circuit condenser O.

The action is as follows. When the frequency of the transmitter varies, the altered beat frequency produces dissimilar currents in the relay windings W, which actuate the monitoring condenser in such a manner as to annul the frequency change. The actuating force on this condenser is zero when the two relay currents are the same, and this current balance is maintained for all amplitudes of the oscillatory-circuit current. The only

* "Automatic Frequency Regulator for Short-Wave Transmitting Stations," *Bulletin de la S.F.R.*, January, 1928.
† Y. KUSONASE and S. ISHIKAWA: "Frequency Stabilization of Radio Transmitters," *Proceedings of the Institute of Radio Engineers*, 1932, vol. 20, p. 310.

effect of a change in amplitude of this current is a slight variation in the frequency sensitivity of the controlling mechanism.

(4) THE RELAY OPERATING CIRCUIT

The function of this part of the apparatus is to provide current to the differential relay operating the monitoring condenser, the magnitude of the current in each winding being dependent upon frequency. The detail design of this operating circuit is dependent chiefly upon the resistance of the relay winding, which in turn is dependent upon the permissible weight of wire. If the frequency-changes to be corrected occur slowly, the moving system of the monitoring condenser may be of appreciable inertia, and consequently a reasonably large quantity of wire may be used, giving a high current-sensitivity. On the other hand, rapid changes of frequency can only be corrected by a moving system having little inertia, and in this case both the weight of wire and the current sensitivity must be reduced. Preliminary experiments

Fig. 2.—Working characteristic of relay operating circuit in automatic monitor.

with a relay winding of 1 000 ohms resistance demonstrated that although great current-sensitivity could be obtained, the inertia of the moving system was too great for practical frequency correction. A suitable compromise was obtained with the winding described in detail in Section (5); this had a resistance of 14 ohms.

For this value of resistance it was found that the most suitable values of the inductance L and capacitance C were 0·05 H and 8 μF respectively. The rectifiers used were Type LT4 Westinghouse metal rectifiers, and the currents in the two relay windings are shown in Fig. 2. The output given by the amplifier was about 150 volts, and a step-down transformer of 7 : 1 was used between the output stage and the operating circuit.

By changing the values of L and C, it is possible to alter the frequency at which the two currents are equal. In Fig. 2 this balance is obtained at a frequency of 405 cycles per sec. An improved control-sensitivity can be obtained by lowering this frequency, but it has been found that if the frequency of the control oscillator differs from that of the transmitter by too small an amount,

there is a possibility that the controlling action may fail if rapid changes in frequency occur. This is due to the inertia of the moving system, which produces a time-lag between the actual frequency-change and the resultant compensating action of the condenser. If this lag is sufficient to enable a zero beat note to exist momentarily, the restoring action fails. It has been found that the lowest satisfactory operating frequency is about 400 cycles per sec. for normal rates of frequency-change, but this value depends largely upon the nature of the frequency-changes and can be altered to suit any particular set of conditions.

(5) THE RELAY MECHANISM

The original form of the electro-mechanical relay consisted of a variable condenser in which the rotor

Fig. 3.—Relay mechanism for automatic monitor.

vane system was moved by means of an armature wound with the two differential windings. The armature was mounted in a magnetic field in a manner similar to that of a moving-coil ammeter, and a torque existed only when the currents in the windings were unequal. In most small-power transmitters, " keying " is effected by stopping and starting the main oscillation, and consequently it is necessary that the monitoring condenser shall remain in any position when the heterodyne beat note controlling the operating circuit disappears during a " space " in keying. This means that the armature must possess no restoring force, a feature which prevents the use of delicate suspension methods of locating the moving system. This requirement makes the design more difficult, since a certain amount of friction in the movement is unavoidable. In the first experimental model appreciable friction was produced by the armature bearings, but in later models it has been reduced considerably. The sensitivity obtained with the original form of monitor mechanism was considerable, owing to the use of high-resistance windings, but the mechanical

inertia was large and the control was limited to cases of slow drifts of frequency. It was realized that the limiting factors for practical operation were mechanical and that a compromise must be made between sensitivity and mechanical inertia.

The present arrangement of the relay mechanism is illustrated in Fig. 3. A radial magnetic field is provided by means of a cylindrical magnet core (1) and iron annulus (2), the excitation being obtained from a winding (3). The magnetic density in the gap is about 10 kilo-lines per cm^2. A light boxwood " former " (4) is located within this field. This " former " acts as a support for the two relay windings X and Y, and also as the support for the moving plate of the monitoring condenser. Each winding consists of 250 turns of 30 S.W.G. doubled-cotton-covered copper wire, the resistance of each being 14 ohms. A light spun aluminium plate (5) forms the moving plate of the condenser and is gummed to the boxwood " former." The lateral strength of this plate is increased by 6 ribs, and the leads to the relay windings are taken through holes in this plate.

The assembly of plate and " former " is mounted on a light brass tube (6) supporting the jewelled bearings (7), and the system is so balanced that the weight is distributed equally on the two bearings. This condenser plate is free to move on the phosphor-bronze spindle (8) which is clamped in position by means of the boss (9) fixed to a rigid insulating support. Connection to this plate is made by a light phosphor-bronze strip (10) to the terminal post A, the main iron frame acting as the fixed plate of the condenser. The maximum and minimum capacitances of this variable condenser are 90 and 40 $\mu\mu$F respectively, giving a total change in capacitance of 50 $\mu\mu$F for a movement of 0·6 in. The total weight of the moving system is 83 grammes.

(6) FREQUENCY STABILITY OBTAINABLE

In order to ascertain the performance of the monitor, it is necessary to produce changes in the parameters of the main oscillation circuit of various amplitude and periodicity to imitate conditions which may arise in practice. For this purpose a special rotating condenser was constructed which produced small sinusoidal changes in the capacitance of the main circuit of the transmitter. The periodicity of this artificial change could be varied by means of a motor drive. The beat frequency produced by the local oscillator heterodyne was recorded by means of a selective circuit operating an Einthoven galvanometer. By this means a photographic record was obtained of the total variation in frequency produced when the monitor was in operation, for each rate of frequency variation. It was found preferable for this purpose to use a balancing frequency of 1 000 cycles per sec., since the monitor behaves more satisfactorily and is not liable to fall out of step. At the lower frequency of 405 cycles per sec. the control is better for slow changes of the circuit parameters. The results of the tests are shown in Fig. 4. In all cases the nominal frequency of the transmitter was 3 000 kilocycles per sec. It will be seen that if the frequency-change is 12 kilocycles per sec. without the monitor control, this change can be reduced to 50 cycles per sec. for slow changes in the circuit parameters, but owing to the large movement of

the monitoring condenser, which takes place with such large changes, the control diminishes as the periodicity is increased. When the rate of frequency variation is 10 times a second, the inertia of the mechanism is such as to give a frequency-change of 200 cycles per sec., and at a rate of variation of 25 times a second it is 450 cycles per sec. At a speed of variation of about 50 times a second, the effect of inertia renders the monitor incapable of operation. When the frequency-change without control is 6 kilocycles per sec., the monitor will control the emitted frequency to an accuracy of 220 cycles per sec. at a periodicity of 25 times a second. This rate of variation is much in excess of any likely changes in practice, and also a 6 kilocycle-per-sec. change in frequency is larger than any drift which is likely to occur in a practical case. For the case of an aerial swinging at the rate of 2 or 3 times a second, the control is of the order of 50 cycles per sec. or 17 parts in 1 million at this operating frequency of 3 000 kilocycles per sec. (100 metres).

An improved performance can be obtained if the
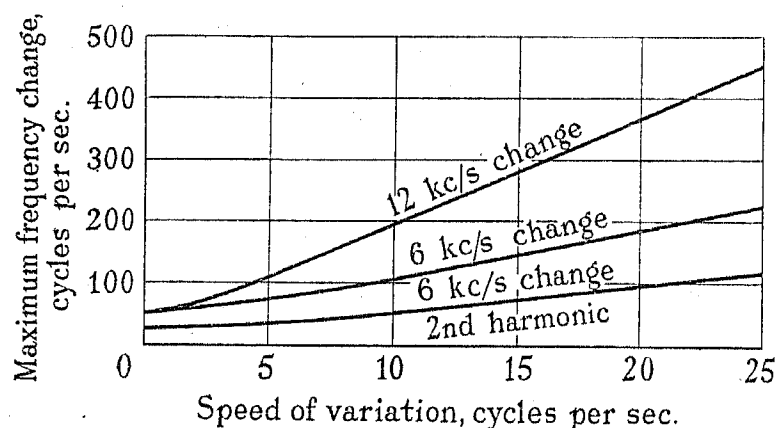
Fig. 4.—Performance of improved monitor control.

master oscillator is made to beat with the second or third harmonic of the transmitter, and when this is done the control is improved by 2 or 3 times respectively. For example, using the second harmonic, a control of 8 parts in 1 million is obtained for low-period changes in the oscillation-circuit parameters.

Although a high degree of frequency stabilization can be attained by the use of a mechanical-monitor control when the oscillatory current in the transmitter is continuous, difficulties may occur when such a system is applied to the frequency control of an oscillator in which the oscillation is interrupted either by anode- or grid-circuit " keying." If, for example, the frequency at the instant of commencement of oscillation differs appreciably from that at the end of the preceding period of oscillation, the monitoring condenser has to move rapidly to a new position, and, owing to its mechanical inertia, a transient frequency-change may thus occur at the " make " of the oscillatory circuit, producing " key chirp " if a normal heterodyne receiver is used. A further possible cause of such " chirps " is the difference in the time-constant of the inductive and capacitative branches of the audio-frequency system. If the current builds up in one of these branches more rapidly than in the other, the differential forces acting on the monitor condenser are not applied simultaneously, and a transient movement

will occur prior to the establishment of the stable controlling condition.

In practice, serious " key chirps " will only arise from the first of these causes if the frequency-drift during a " space " in keying approaches the controlling audio-frequency of the system; this means that the frequency-change must be about 1 kilocycle per sec. in a time of about 0·1 sec. for hand keying, and such rapid changes of frequency are unlikely to occur in normal operation. This difficulty can, of course, be overcome if the oscillation is maintained during a " space " in keying, which necessitates the use of an aerial-circuit key. This solution is, however, impracticable except for very small values of aerial current.

Any such " key chirp " can of course be entirely eliminated by the use of a method of reception in which a signal of constant audio-frequency is " triggered " by the transmission. One such system* was tried and proved successful, but an alternative arrangement giving a higher sensitivity is described in the Appendix.

It is not suggested that this or any similar method of reception, with its associated disadvantage of a lack of audio-frequency discrimination, is essential to successful reception of an automatically monitored transmission, since experiment has shown that only in very exceptional circumstances will this " key chirp " be sufficiently pronounced to make reception difficult.

(7) CONCLUSION

It has been shown that an automatic monitor forms a satisfactory means of stabilizing the frequency of a transmitter for comparatively large and rapid changes in the parameters of the oscillation circuit. The degree of frequency stabilization obtainable is of the order of 5 parts in 1 million for working frequencies of about 3 000 kilocycles per sec. if the rate of change of the circuit parameters is slow. For changes in frequency at a rate of variation of 25 times a second, the monitor will reduce a 6 kilocycle-per-sec. change to 0·1 kilocycle per sec., corresponding to 30 parts in 1 million at a working frequency of 3 000 kilocycles per sec.

The system is satisfactory for telegraphic transmission using normal anode- or grid-circuit keying, provided the frequency drift which would take place if the system was uncontrolled does not exceed about 500 cycles per sec. during a period of cessation of oscillations. Under these conditions the control is similar to that defined above, irrespective of the total frequency drift, but key " chirps " may be present. If the uncontrolled frequency-drift during the period of cessation of oscillations exceeds 500 cycles per sec., satisfactory control can only be obtained by using aerial circuit keying, the stability obtainable being the same as before.

For the complete elimination of key chirps it may be necessary to use a system of reception which gives a constant audio-frequency output that is independent of the frequency of the received signal. Such a system has been tried and has been found satisfactory.

The work described in this paper was carried out as part of the programme of the Radio Research Board and is published by permission of the Department of Scien-

* M. REED: "Some Applications of an A.C. Valve Bridge," *Electrical World*, 1934, vol. 11, p. 175.

tific and Industrial Research. The author is indebted to Dr. R. L. Smith-Rose and Mr. F. M. Colebrook for valuable advice in the presentation of the paper, and to Mr. A. C. Haxton for his assistance in the experimental work.

APPENDIX

Suggested Mode of Reception to avoid " Key Chirps "

One means of producing a constant-frequency telephone signal is that in which a balanced bridge system
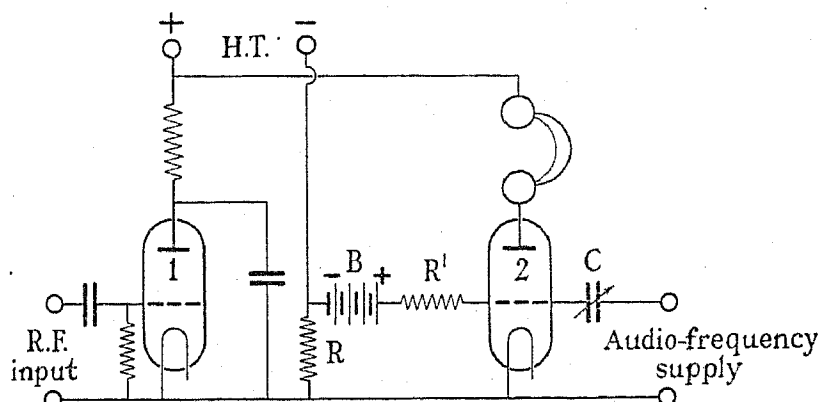
Fig. 5

supplied from an audio-frequency source is unbalanced by a current derived from the radio-frequency signal e.m.f. This was tried and found to be successful, but the system shown in Fig. 5 proved to be more sensitive. The triode (1) and its associated circuit form a simple grid-circuit rectifier. The anode current develops a potential difference across the resistance R, and this potential is used as bias for a second valve (2). The grid of this valve is supplied with a constant-frequency potential by means of an audio-frequency oscillator, and the value of this potential can be varied by means of the divider R'C. The large negative potential applied
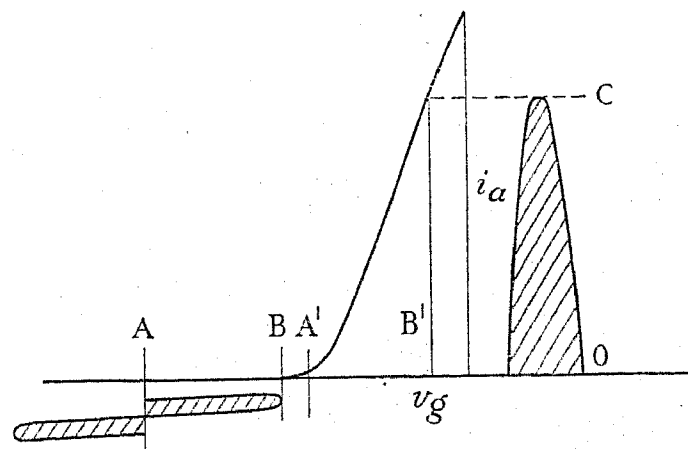
Fig. 6

to the grid of this valve is reduced by the series battery B. Referring to Fig. 6, the voltage of this battery, together with the value of R, is so adjusted as to give a normal negative potential corresponding to point A on the v_g/i_a characteristic. The amplitude of the audio-frequency potential is adjusted to a value AB such that no anode current flows in the telephones. When a radio-

frequency signal is applied to the rectifier, the anode current falls and the mean potential of the grid of valve 2 rises to a new value A'. The audio-frequency potential of constant amplitude and frequency now gives a grid excursion from A' to B' corresponding to an anode current of peak value OC, which produces a signal in the telephones.

It has been found in a laboratory test that such a system of reception is quite satisfactory and can give loud-speaker strength if one further stage of amplification is added. The sensitivity is, in fact, of the same order as that of a normal amplifier employing the same number of valves. It is suggested that such a method of reception could be used as an alternative to the usual heterodyne arrangement when the transient frequency variations are such as to produce "key chirps" in the receiving telephones of such magnitude as to render reception difficult.

DISCUSSION ON

"APPLICATIONS OF THE HOT-CATHODE GRID-CONTROLLED RECTIFIER, OR THYRATRON"*

WESTERN CENTRE, AT CARDIFF, 9TH MARCH, 1936

Mr. J. B. J. Higham: I should like to know whether it is possible to use the thyratron in the rotor circuit of a slip-ring induction motor for the purpose of power-factor improvement.

Regarding inverted running, is the thyratron subject to the limitations of the mercury-arc rectifier, in that it must be connected to an existing a.c. system?

Mr. H. M. Roberts: I should like to have further information as to the signs of approaching failure of a thyratron. In the case of a thyratron-controlled variable-speed d.c. motor for a strip mill, would the failure be instantaneous or would one receive a fair amount of warning? If the failure were instantaneous then I can foresee that a good deal of wastage of material would take place.

Mr. C. W. Pitcher: I should like to inquire into the possibilities of the use of the thyratron as a high-speed circuit breaker. Also, what is the reason for the upper limit of frequency mentioned by the author?

Mr. H. G. Weaver: Mr. Roberts has mentioned the control of large d.c. motors; I should like to ask the author whether the thyratron could be made to control a continuous strip mill, where it would be required to keep large variable-speed d.c. motors at an absolutely constant speed regardless of load.

Mr. A. L. Whiteley (*in reply*): In reply to Mr. Higham's question as to the possibility of using thyratrons to improve the power factor of an induction motor, there are both practical and theoretical difficulties. The practical difficulties exist because the rotor circuit of an induction motor carries high currents at such a low voltage that any form of mercury-arc rectifier would be at a disadvantage. Further, if the induction motor were required to run near its synchronous speed, step-up transformers to the rectifier would be out of the question as the frequency of the rotor currents would be only a few cycles per second. A synchronous motor would present a more satisfactory solution, even if the above-mentioned difficulties did not exist. If, in addition, Mr. Higham has in mind speed control of an induction motor, I would remind him that a thyratron cannot be looked upon as a variable a.c. impedance. It is therefore not feasible to replace a resistance in the rotor of an induction motor by thyratrons. If speed control of a large a.c. motor is required, then the thyratron commutator motor† provides one method. In effect this is a synchronous motor operated from an a.c. supply of constant frequency, through the medium of a thyratron frequency-changer.

Turning to Mr. Higham's second question, the thyratron has precisely the same basic limitations as the mercury-arc rectifier, both as a rectifier and as an invertor. As Mr. Higham suggests, it is desirable that a grid-controlled invertor should feed into an a.c. system either in parallel with a.c. generators or with a synchronous load. The invertor is then what is known as "line excited," i.e. the line voltage can be made effective to transfer current from one anode to the next in the correct order. It is not essential, however, that this current commutation should be effected by an external e.m.f. Various commutating schemes have been suggested and tried out for self-excited invertors; in general, capacitance is used, in either a series or a parallel connection in the main anode circuit. Unfortunately, the capacitance of the commutating condenser (or condensers) is high, the kVA rating being of the same order as that of the invertor itself.

Mr. Roberts asks for information as to signs of approaching failure of a thyratron. Failure is usually brought about by reduced cathode emission, or by the presence of a gas other than the mercury vapour, or correct gas filling. In the case of tubes having directly-heated cathodes, an increase in arc drop (i.e. the potential difference between anode and cathode during firing of the arc) often precedes failure. Unfortunately, the

* Paper by Mr. A. L. WHITELEY (see page 516).

† E. F. W. ALEXANDERSON and A. H. MITTAG: "The Thyratron Commutator Motor," *Electrical Engineering*, 1934, vol. 53, p. 1517.

larger tubes having indirectly-heated cathodes do not give this preliminary warning. Nevertheless, occasional inspection of thyratrons will do much to eliminate unexpected failures. The ionization glow of a " healthy " mercury tube is blue in colour; it is also a good sign if the ionization-glow is confined to the inter-electrode space between anode and cathode. Presence of gaseous impurities in the mercury vapour is frequently indicated by an ionization glow which is of a reddish tint. Other visual signs of impending failure are sometimes given. The present tendency is towards the complete enclosure of the inter-electrode space by means of a large control grid; whilst the electrical characteristics of the tube are thereby improved, inspection of the arc is unfortunately made more difficult. Mr. Roberts mentions an application which requires a high degree of reliability; I would therefore suggest a parallel connection of tubes in such an instance (see Fig. D in my reply to the discussion at London).

Mr. Pitcher inquires as to the possibility of using a thyratron as a high-speed circuit breaker. It could be used as such in an a.c. system, and would have the advantage that the current might be interrupted within half a cycle, and with the minimum disturbance to the system. The kVA rating of the largest available size of thyratron is, however, much too low to permit its use as a circuit breaker on a power system. It is in somewhat special applications such as the welding control system described in the paper, involving a high frequency of circuit interruption, where the thyratron shows up to advantage as a circuit breaker.

In answer to Mr. Pitcher's second question, the upper limit of frequency of a thyratron rectifier or invertor is set by what is known as the de-ionization time. After the arc has been extinguished owing to the lowering of the anode potential to zero, positive ions are left in the tube. These must be removed in order that the grid may regain control, i.e. they must be removed before the anode becomes positive again. The de-ionization time is largely a function of tube design, but also depends upon grid-circuit regulation and the magnitude of the anode load. It is measured in microseconds, and very approximate figures are 100 for an invertor type and 1 000 for a standard industrial control type of thyratron.

I would remind Mr. Weaver that it is a very controversial point as to whether very close speed regulation of a continuous strip mill is actually required. This partly explains why thyratron control of a d.c. mill motor has not been attempted. It would, however, be quite within the possibilities of a thyratron speed regulator to maintain the speed within 1 per cent from no load to full load. As, however, a continuous strip mill motor is likely to be the order of 2 500 h.p., it would be preferable to control the main field through an exciter. The thyratrons would supply excitation to the field of the latter. I do not think that there need be any difficulty due to speed of response of such a system.

PROCEEDINGS OF THE INSTITUTION

892ND ORDINARY MEETING, 2ND JANUARY, 1936

Mr. J. M. Kennedy, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 19th December, 1935, were taken as read and were confirmed and signed.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

The President announced that, during the month of December, 61 donations and subscriptions to the Benevolent Fund had been received, amounting to £208. A vote of thanks was accorded to the donors.

A paper by Mr. A. L. Whiteley, M.Sc., Associate Member, entitled "Applications of the Hot-Cathode Grid-Controlled Rectifier, or Thyratron " (see page 516), was read and discussed.

A vote of thanks to the author, moved by the President, was carried with acclamation.

893RD ORDINARY MEETING, 16TH JANUARY, 1936

Mr. J. M. Kennedy, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 2nd January, 1936, were taken as read and were confirmed and signed.

The President announced that the Council had elected Sir John F. C. Snell, G.B.E., an Honorary Member of the Institution, and that the fourteenth award of the Faraday Medal had been made to Sir William H. Bragg, O.M., K.B.E., M.A., D.Sc., F.R.S.

Messrs. L. L. Tolley and D. V. Wilton were appointed scrutineers of the ballot for the election and transfer of members and, at the end of the meeting, the President reported that the members whose names appeared on the lists (see page 252), had been duly elected and transferred.

The following list of donors to the Library was taken as read, and the thanks of the meeting were accorded to them: The Actino Press, Ltd.; Academy of Sciences of the U.S.S.R.; Air Ministry; G. Alliata; American Institute of Electrical Engineers; American Radio Relay League, Inc.; American Society of Mechanical Engineers; Association of Engineers in Burma; Association of

Municipal Electrical Engineers, South Africa; The Astronomer Royal; Ateliers de Constructions Électriques de Charleroi; Australian Radio Research Board; Messrs. Babcock and Wilcox, Ltd.; E. H. W. Banner, M.Sc.; H. de Bellescize; Messrs. Benn Bros., Ltd.; Messrs. Bennis and Co., Ltd.; W. J. Birnie; Board of Education; D. J. Bolton, M.Sc.(Eng.); S. M. Bower; British Aluminium Co., Ltd.; British Broadcasting Corporation; British East African Meteorological Service; British Electrical and Allied Industries Research Association; British Engine, Boiler, and Electrical Insurance Co., Ltd.; British Standards Institution; C. A. Cameron Brown, B.Sc.; Building Industries National Council; W. E. Burnand; Albert Campbell, M.A.; Canadian Bureau of Statistics; Canadian Government Trade Commissioner; Carnegie United Kingdom Trustees; Carriers Publishing Co., Ltd.; Caxton Publishing Co., Ltd.; Central Electricity Board; Ceylon Government Department of Electrical Undertakings; H. J. Barton Chapple, B.Sc.(Eng.); Chemical Rubber Publishing Co.; The Chief Inspector of Factories and Workshops; " The Colliery Guardian "; Comité International des Tables Annuelles de Constantes et Données Numeriques; Messrs. Constable and Co., Ltd.; Copper Development Association; Messrs. Crosby Lockwood and Son, Ltd.; Danmarks Naturvidenskabelige Samfund; Dansk Ingeniorforening; Department van Verkeer en Waterstaat, Bandoeg; Derby Society of Engineers; F. J. Down; Messrs. Dunod; Electric Supply Authority Engineers' Association, New Zealand; Electrical Association of Japan; Electrical Association for Women; The Electricity Commissioners; Electricity Supply Commission of South Africa; C. F. Elwell; Messrs. Eyre and Spottiswood (Publishers), Ltd.; Federation of British Industries; L. Ferrand; French Embassy (Commercial Attaché); Messrs. Gee and Co. (Publishers), Ltd.; General Electric Co., Ltd.; G.P.O. Public Relations Department; K. Hedges; Helsinke Municipal Electricity Works; The High Commissioner for India; High Speed Steel Alloys, Ltd.; E. S. Hodges; L. E. C. Hughes, Ph.D.; Hull Association of Engineers; Hydro-Electric Commission, Tasmania; Hydro-Electric Power Commission, Ontario; Messrs. Iliffe and Sons, Ltd.; Imperial Institute; Incorporated Municipal Electrical Association; Indian Posts and Telegraphs Department; Institute of Electrical Engineers of Japan; Institute of Television Engineers of Japan; Institute for Research in Agricultural Engineering, Oxford; Institution of Automobile Engineers; Institution of Civil Engineers; International Electrotechnical Commission; International Tin Research and Development Council; Iron and Steel Institute; Messrs. Johnson and Phillips, Ltd.; Leeds Association of Engineers; Lincoln Engineering Society; M. G. Lloyd; Lloyd's Register of Shipping; London and Home Counties Joint Electricity Authority; Messrs. Macdonald and Evans; McGraw-Hill Publishing Co., Ltd.; S. J. Matthews; Metropolitan-Vickers Electrical Co., Ltd.; Mines Department; E. Molloy; Murex Welding Processes, Ltd.; Messrs. George Newnes, Ltd.; National Power Survey, U.S. Federal Power Commission; New Zealand Post and Telegraphs Department; Norwegian Watercourse and Electricity Department; F. C. Orchard; H. Parodi; P. O. Pedersen; Messrs. Sir Isaac Pitman and Sons, Ltd.; Rand Water Board, S.A.; E. T. A. Rapson; Research Association of British Rubber Manufacturers; Reale Accademia d'Italia; J. H. Reyner, B.Sc.; H. Rissik, B.Sc.(Eng.); R. A. Rothermel; Royal Alfred Observatory, Mauritius; A. Rubin; M. G. Scroggie, B.Sc.; Sixth International Congress for Scientific Management; Prof. S. P. Smith, D.Sc.; Società Edison, Milan; Société Financière de Transport et d'Enterprises Industrielles; Société Française des Électriciens; Société Française Radio-Électrique; Messrs. E. and F. N. Spon, Ltd.; Standards Association of Australia; Svenska Teknologforeningen; M. G. S. Swallow; F. H. Taylor; The Technical Press, Ltd.; H. C. Turner; H. Waddicor, B.Sc.; R. C. Walker, B.Sc.; Warsaw Polytechnic Institute; Messrs. C. A. Watts, Ltd.; Messrs. Wightman and Co., Ltd.; G. Windred; and Wirtschaftsgruppe Elektroindustrie.

A paper by Mr. A. C. Timmis, B.Sc., Associate Member, entitled " Recent Developments in Long-Distance Telephony " (see page 601), was read and discussed. The paper was illustrated by a short cinematograph film.

A vote of thanks to the author, moved by the President, was carried with acclamation.

894TH ORDINARY MEETING, 30TH JANUARY, 1936

Mr. J. M. Kennedy, O.B.E., President, took the chair at 6 p.m.

The minutes of the Ordinary Meeting held on the 16th January, 1936, were taken as read and were confirmed and signed.

The President then read a Resolution (see page 121), which had been passed at a special meeting of the Council, on the death of His Majesty King George V. The Resolution was confirmed in silence, all present standing.

A list of candidates for election and transfer, approved by the Council for ballot, was taken as read and was ordered to be suspended in the Hall.

A paper by Messrs. W. L. McPherson, B.Sc.(Eng.), and E. H. Ullrich, M.A., entitled " Micro-Ray Communication " (see page 629), was read and discussed.

A vote of thanks to the authors, moved by the President, was carried with acclamation.

PATRON OF THE INSTITUTION

His Majesty the King has been graciously pleased to grant his Patronage to the Institution.

INDEX TO JOURNAL

Any member who proposes to bind the current volume of the *Journal* and would like to have an extra copy of the Index, for filing apart from the bound copy of the *Journal*, can obtain an additional copy on application to the Secretary.

ELECTRICAL ENGINEERS' BALL

The Committee of Management of the Benevolent Fund are glad to say that the Fund has benefited to the extent of £230 1s. 5d., this being the surplus available after defraying all the expenses of the Ball held on the 14th February last. The attendance was over 1 050.

BEHREND MEMORIAL GIFT

The Institution has received from Mrs. B. A. Behrend a collection of textbooks and a number of volumes of *Nature* which formerly belonged to Oliver Heaviside and which contain numerous marginal annotations by him. The gift is in memory of her husband, the late Dr. B. A. Behrend of Massachusetts, U.S.A., and includes four autograph letters from Heaviside to Dr. Behrend.

The presentation was announced by the President at the Faraday Lecture on the 7th May, and he conveyed the thanks of the members to Mrs. Behrend, who was present, for her generous gift. It is a source of gratification to the Council to know that by the acquisition of these books the Institution now appears to possess the entire collection of textbooks which formed Heaviside's library.

COMMUNICATIONS FROM OVERSEAS MEMBERS

Overseas members are especially invited to submit for publication in the *Journal* written communications on papers read before the Institution or published in the *Journal* without being read. The contributor's country of residence will be indicated in the *Journal*. In this connection a number of advance copies of all papers read before the Institution are sent to each Local Hon. Secretary abroad to enable him to supply copies to members likely to be in a position to submit communications.

MEMBERS FROM OVERSEAS

The Secretary will be obliged if members coming home from overseas will inform him of their addresses in this country, even if they do not desire a change of address recorded in the Institution register.

The object of this request is to enable the Secretary to advise such members of the various meetings, etc., of the Institution and its Local Centres, and, when occasion arises, to put them into touch with other members.

During the period 1st March to 31st May the following members from overseas called at the Institution and signed the "Attendance Register of Overseas Members":—

Adcock, W. H., B.Sc. (*Calcutta*).
Anderson, F. C. K. (*Barbados*).
Baker, E. W. (*Chittagong, India*).
Baly, W. F., B.Sc.(Eng.) (*Buenos Aires*).
Bellamy, L. C. F., M.C. (*Hong-Kong*).
Clark, H., B.Sc. (*Durban*).
Crowcroft, H. E. (*Shanghai*).
Gibson, F. H. (*Penang*).
Greenwood, E. J. B. (*Madras*).
Hale, T. C. (*Surat*).
Handyside, J. S. (*Auckland, N.Z.*).
Khanna, J. (*Bombay*).
Kirk, G. L. (*Colombo*).
Lee, J. H., M.C., B.Sc. (Eng.) (*Wellington, N.Z.*).
Meek, J., Jun., B.Sc.(Eng.) (*Madras*).
Moscardo, F. (*Valencia*).
Murray, C., B.Sc.(Eng.) (*Calcutta*).
Park, R. T. (*Madras*).
Parker, W. J. (*Trujillo, Peru*).
Phillips, H. A. (*Penang*).
Rendell, L. M. (*Delhi*).
Richards, C. G., M.Sc.Tech. (*Singapore*).
Roe, G. E. (*Nairobi*).
Sharpe, H. A. (*Lahore*).
Talbot-Jones, R. V. (*Pretoria*).
Warren, H. (*Shanghai*).

COUNCIL'S NOMINATIONS FOR ELECTION TO THE COUNCIL

The following have been nominated by the Council for the vacancies which will occur in the offices of President, Vice-President, Honorary Treasurer, and Ordinary Members of Council, on the 30th September, 1936:—

President. (*One Vacancy.*)
H. T. Young.

Vice-President. (*One Vacancy.*)
Johnstone Wright.

Honorary Treasurer. (*One Vacancy.*)
F. W. Crawter.

Ordinary Members of Council.
MEMBERS. (*Five Vacancies.*)

T. Carter.	C. E. Fairburn, M.A.
H. J. Cash.	F. Forrest.
S. W. Melsom.	

Associate Member. (*One Vacancy.*)
C. R. Westlake.

Associate. (*One Vacancy.*)
E. M. Lee.

PREMIUMS

The Council have made the following awards of Premiums for papers read or accepted for publication only:—

The Institution Premium (value £25).

W. L. McPHERSON, B.Sc.(Eng.), and E. H. ULLRICH, M.A. "Micro-Ray Communication."

The Ayrton Premium (value £10).

G. H. WILSON, B.Sc. (Eng.), Lieut.-Commander E. L. B. DAMANT, R.N. (Ret.), and J. M. WALDRAM, B.Sc.(Eng.). "The High-Pressure Mercury-Vapour Lamp in Public Lighting."

The Fahie Premium (value £10).

Major L. H. PETER, A.F.C., M.C. "Modern Developments in Railway Signalling."

The John Hopkinson Premium (value £10).

D. R. DAVIES and C. H. FLURSCHEIM, B.A. "The Development of the Single-Break Oil Circuit-Breaker for Metalclad Switchgear."

The Kelvin Premium (value £10).

T. E. ALLIBONE, Ph.D., M.Sc., and F. R. PERRY, M.Sc.Tech. "Standardization of Impulse-Voltage Testing."

A Premium (value £5).

B. G. GATES, B.Sc. "Neutral Inversion in Power Systems."

A Premium (value £5).

E. T. HIPPISLEY, M.A. "The Choice of Electric Traction-Motor Equipment by the Method of Similar Speed/Time Curves."

A Premium (value £5).

E. R. KAAN "Main-Line Electrification throughout the World, with special reference to the Austrian Federal Railways."

A Premium (value £5).

R. POOLE "The Design of Large Electrical Machine Frames."

A Premium (value £5).

RUSSELL J. REYNOLDS, C.B.E., M.B., B.S., M.R.C.P. "Cineradiography."

A Premium (value £5).

A. C. TIMMIS, B.Sc. "Recent developments in Long-Distance Telephony."

A Premium (value £5).

G. A. WHIPPLE, M.A. "A Cathode-Ray Oscillograph with High-speed Drum Camera rotating in Vacuo."

A Premium (value £5).

A. L. WHITELEY "Applications of the Hot-Cathode Grid-Controlled Rectifier or Thyratron."

An Overseas Premium (value £5).

J. J. RUDRA, M.A., Ph.D. and D. J. BADKAS, M.Sc. "The Theory, Performance, and Calculations, of a Polyphase Capacitor-Type Motor."

An Overseas Premium (value £5).

J. H. SPRAWSON "Experience and Conclusions of the Running of the Cape Town–Simonstown Electrification of the South African Railways."

An Overseas Premium (value £5).

T. VARNEY, B.Sc. "Vibration in Overhead Conductors."

Wireless Section Premiums

The Duddell Premium (value £20).

H. L. KIRKE and A. B. HOWE, M.Sc. "The Acoustical Design of Broadcasting Studios."

A Premium (value £10).

W. J. BROWN, B.Sc. "Considerations in the Design of a High-Fidelity Radiogramophone."

A Premium (value £10).

E. G. MOULLIN, M.A. "The Radiation Resistance of Aerials whose Length is comparable with the Wavelength."

Meter and Instrument Section Premiums

The Silvanus Thompson Premium (value £20).

J. H. BUCHANAN, B.Sc. "The Design, Construction, and Testing, of Voltage Transformers."

A Premium (value £10).

Prof. J. T. MacGREGOR-MORRIS and R. M. BILLINGTON, M.Sc. (Eng.). "The Selenium Photo-Rectifier Cell: its Characteristics and Response to Intermittent Illumination."

A Premium (value £5).

J. S. PRESTON, M.A. "The Selenium Rectifier Photocell: Manufacture, Properties, and Use in Photometry."

A Premium (value £5).

G. A. BURNS and T. R. RAYNER "Remote Control of Power Networks."

Transmission Section Premiums

The Sebastian de Ferranti Premium (value £20).

D. Ross — " A Review of Recent Developments in Rural Electrification."

A Premium (value £10).

J. S. Forrest, M.A., B.Sc. — " The Electrical Characteristics of 132-kV Line Insulators under Various Weather Conditions."

The awards for papers read before the Students' Sections will be announced later.

PROCEEDINGS OF THE WIRELESS SECTION

124TH MEETING OF THE WIRELESS SECTION, 6TH NOVEMBER, 1935

Mr. S. R. Mullard, M.B.E., Past-Chairman, took the chair at 6 p.m.

The minutes of the meeting held on the 13th May, 1935, were taken as read and were confirmed and signed.

Mr. Mullard announced the Council's award of Premiums (see vol. 76, page 718) for papers read before the Section during the session 1934–35. He then vacated the chair, which was taken by the new Chairman of the Section, Mr. R. A. Watson Watt, B.Sc.(Eng.).

A vote of thanks to Mr. Mullard for his services as Chairman during the session 1934–35, proposed by Sir Noel Ashbridge and seconded by Mr. A. J. Gill, B.Sc.(Eng.), was carried with acclamation.

Mr. Watson Watt welcomed the foreign delegates of the International Special Committee on Radio Interference who were present at the meeting. He then delivered his Inaugural Address (see page 10).

A vote of thanks to the Chairman for his Address, proposed by Mr. Mullard, was carried with acclamation.

4TH INFORMAL MEETING OF THE WIRELESS SECTION, 26TH NOVEMBER, 1935

Chairman: Mr. R. A. Watson Watt, B.Sc.(Eng.).

Subject of Discussion: " Standardizing Performance of Broadcast Radio Receivers " (opened by Dr. R. L. Smith-Rose).

Speakers: Messrs. L. E. C. Hughes, Ph.D., P. K. Turner, G. Bradfield, F. Murphy, B.Sc.(Eng.), —. Needham, H. E. Strathers, —. Hill, W. B. Bartley, —. Crawter, J. M. Smith, —. Thompson, H. A. Thomas, M.Sc., J. Joseph, R. A. Watson Watt, B.Sc.(Eng.), and W. D. Owen.

125TH MEETING OF THE WIRELESS SECTION, 3RD DECEMBER, 1935

Mr. R. A. Watson Watt, B.Sc.(Eng.), Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 6th November, 1935, were taken as read and were confirmed and signed.

A paper by Messrs. H. L. Kirke, Associate Member, and A. B. Howe, M.Sc., entitled " The Acoustical Design of Broadcasting Studios " (see page 404) was read and discussed. A vote of thanks to the authors, moved by the Chairman, was carried with acclamation.

126TH MEETING OF THE WIRELESS SECTION, 8TH JANUARY, 1936

Mr. R. A. Watson Watt, B.Sc.(Eng.), Chairman of the Section, took the chair at 6 p.m.

The minutes of the meeting held on the 3rd December, 1935, were taken as read and were confirmed and signed.

A paper by Mr. E. B. Moullin, M.A., Associate Member, entitled " The Radiation Resistance of Aerials whose Length is Comparable with the Wavelength " (see page 540), was read and discussed. A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

5TH INFORMAL MEETING OF THE WIRELESS SECTION, 14TH JANUARY, 1936

Chairman: Mr. R. A. Watson Watt, B.Sc.(Eng.).

Subject of Discussion: " Ultra-Short Waves for Broadcasting " (opened by Sir Noel Ashbridge).

Speakers: Messrs. P. P. Eckersley, N. H. Smith, M. G. Scroggie, B.Sc., E. J. Alway, B. S. Gossling, P. G. A. H. Voigt, B.Sc.(Eng.), —. Gapp, H. Bishop, B.Sc.(Eng.), W. F. Floyd, B.Sc., W. M. Dalton, C. E. G. Bailey, B.A., J. A. Cooper, O. S. Puckle, H. J. Howlgate, E. H. Ullrich, M.A., and R. A. Watson Watt, B.Sc.(Eng.).

ELECTIONS AND TRANSFERS

At the Annual General Meeting of the Institution held on the 7th May, 1936, the following elections and transfers were effected:—

Elections

Associate Members

Ailleret, Pierre Marie J.
Elliott, Norman Randall, B.A.
Evans, Ivor Griffith.
Fraser, David Mann.
Hadfield, Wilfred, B.A.
Hammett, Edwin John.
Jordan, Ernest.
Lubowsky, Edgar Kurt, Dr.Ing.
MacEwan, Harry Camden.
Meek, Leonard.
Mozumdar, Dhirendra Nath, B.Sc.
Peters, Harold, B.Sc.(Eng.).
Quinton, Henry, B.Sc.
Roy, David Walter.
Shivapuri, Pandit Ratan N.
Waite, Griffin Grante, B.Sc.(Eng.).

Associates

Frankland, Charles Hayes.
Mansfield, John Archibald.
Middleton, Walter James D.
Mills, Charles Frederick.
Morgan, Edward Henry.
Nye, Douglas Harvey.

Graduates

Bathgate, Robert James F., B.Sc.(Eng.).
Berry, Hugh William.
Bhimjee, Sher Ali.
Catchpole, Thomas Denny H., B.Sc.(Eng.).
Gill, Pritam Singh.
Hardick, Norman, B.Sc. (Eng.).
Judson, John Lister.
Leake, Henry Arthur.
Newman, Stanley Frederick, B.Sc.(Eng.).
Nicholson, John.
Pelton, Bruce Sydney, B.Sc.(Eng.).
Sanders, James Curtice.
Surveyor, Behman Navroji.
Taylor, Leslie James, B.Sc.
Wynne, Walter Lewis L., B.A.

Students

Ahuja, Gopal K.
Allen, Henry William S.
Barber, Ernest George, B.Sc.(Eng.).
Bardens, Arthur Thomas B.
Beardmore, Eugene Charles.
Booth, Sydney Pearson.
Broacha, R. H.
Brown, William Henry.
Brownbridge, Gilbert Arthur.
Buxton, Harry Livesey.
Carrothers, John Kelly.
Child, Stanley.
Collins, Philip Thomas.
Crawshaw, Geoffrey.
Driver, Walter Stanley.
Ewin, Desmond Ellison.
Furzey, Jack.
Gray, George Alexander.
Grimsey, Arthur William.
Hall, James Peter.
Hanham, Bernard Edmund.
Hinds, John Arnold.
Holmes, Alfred Conyers.
Hudson, Albert Raymond.
Jones, Ivor Roderick L.
Jones, Stanley.
Jordan, George Noel.
Lamplough, John Stewart.
Lang, George Andrew.
Leigh, Bertram Robert, B.Sc.
Linn, William Adam.
Little, James McKee.
Lloyd, William John.
McEvoy, John.
Messenger, Harold.
Miles, James William.
Mills, Russell Alberto.
Minto, S. K. H.
Mistry, Rustom Dhanjibhoy.
Morgan, John Graham.
Morrice, Ronald Alexander.
Mouat, William Neils.
Munro, Alexander.
Nicholls, John Beresford.
Passmore, Cyril James.
Patrick, Ernest.
Penberthy, Arthur Frederick.
Perry, William Henry.
Philippos, Matthai.
Rao, N. R. Ramachandra.
Razvi, S. K. H.
Reekie, Gavin Ralston.
Rees, Thomas Raymond.
Rhodes, John Blades.
Robinson, Cyril.
Rogers, Harold James.
Shepherd, Herbert Norman.
Smith, Ambrose Charles.
Smith, Jonathan William.
Smith, William Edward.
Smither, Harold.
Srinivasiengar, Kadaba Rangiengar, M.Sc.
Tagholm, John Edward.
Wade, Walter Ralph.
Whalley, Geoffrey.
White, Lionel Harry A.
Williams, Thomas Arthur.
Williamson, Drummond.
Winfield, Norman.
Wolfenden, Ronald Harcourt.
Worman, Eric Frank.

Transfers

Associate Member to Member

Colyer, James Frederick H.
Ellis, Richard Milward.
Kennett, William Charles, B.Sc.(Eng.).
Kipping, Norman Victor.
Smith-Rose, Reginald Leslie, D.Sc., Ph.D.
Sumner, John Arthur.
Ward, Bernard Cecil P.

Associate to Associate Member

Barrows, Edmund John.
Grimmitt, Howard Walker.
Lawrence, Robert.
May, Kenneth Lawrence.
Mills, Arthur George.
Schofield, Hubert Vane.

Graduate to Associate Member

Balasuriyar, Muthiah Muthu, B.Sc.(Eng.).
Bowers, Laurence.
Bowles, Charles.
Brown, Jack Keyes, B.Sc.
Clark, Henry Arthur M.
Cliff, James Stanley.
Comben, Walter Frederick.
Curran, Reginald John H.
Davis, Robert Courtney.
Deutsch, Alfred.
Finden, Harold Jack.
Gettliffe, Rupert, B.Sc. (Eng.).
Giles, Percy Albert.
Hadfield, Bertram Morton, B.Sc.(Eng.).
Hale, Thomas Charles.
Harvey, Robert Antony, B.Sc.(Eng.).
Haworth, William Ernest.
Jeffcock, Robin John P.
Lackie, William Robson.
Lappin, Henry.
Law, Lionel William, M.A.
Lawrance, Walter Francis C.
Osman, Abdelsalam Ahmad, M.Sc.
Pierce, David Francis.
Prince, Harry Leslie.
Raybould, Sidney.
Rudd, Charles George, M.Sc., B.E.
Sharples, John Thomas, B.Sc.Tech.
Skinner, Charles Henry W., B.Sc.(Eng.).
Veevers, John Foster.
Whipple, George Allan, M.A.
Yarwood, Henry Ivens, B.Sc.

The following transfers were also effected by the Council at their meeting held on the 23rd April, 1936:—

Student to Graduate

Adlard, Wyndham Roy.
Balean, Henry Hamilton.
Berridge, Edward John.
Bradford, Basil John.
Brewster, Harry George, B.Sc.(Eng.).
Calderara, Peter.
Clapham, Harold Edward C.
Cozens, William James, B.Sc.
Davy, Granville Vernon, B.Sc.(Eng.).
Doel, Ralph Francis, B.Sc.
Dugdale-Bradley, John Oliver.
Fattal, Ezra E., B.Sc.
Garrard, Robert William.
Hibell, Arthur Richard.
Hindess, Henry Gordon.
Howe, Ronald Lloyd.
Kilby, Herbert.
Kilvington, Thomas, B.Sc.(Eng.).
Lambert, Albert Peters.
Langford, Cyril Etheridge R., B.Sc.
Lavarack, Terence Vaughan.
Lucas, John Harold, B.Sc.(Eng.).
McIntosh, Howie James, B.E.
Midgley, Frank.
Millyard, Harold.
Narain, Harendra, B.Sc.
Nerurker, Ganpat Janardan.
Padaki, Seshagirirao Sreenivasarao.
Tapson, Ernest Lionel.
Taylor, Percy Heatley, B.Sc.(Eng.).
Tillekeratne, Thomas Stanley V.
Tomlin, Herbert Stanley, B.Sc.(Eng.).
Whitmore, Scovell Frederick C.

Supervisory and Remote Control Systems

ANOTHER WESTINGHOUSE ACHIEVEMENT

By the use of a special patented circuit, Westinghouse Metal Rectifiers are now offered for feeding projector arcs, with the following very important advantages: (1) No resistances of any description are needed, allowing (2) a very high efficiency and (3) an extremely good power factor, to be obtained; (4) the equipment is entirely in duplicate as regards the power circuits so that (5) the operation of one arc in no way affects the performance of the other; (6) the equipment is compact and self-contained, and needs no foundations; (7) it can be started instantaneously; (8) it is free from vibration; (9) it cannot radiate interference; (10) it is trouble-free and (11) needs no attention or supervision, and there are (12) no glass bulbs to renew.

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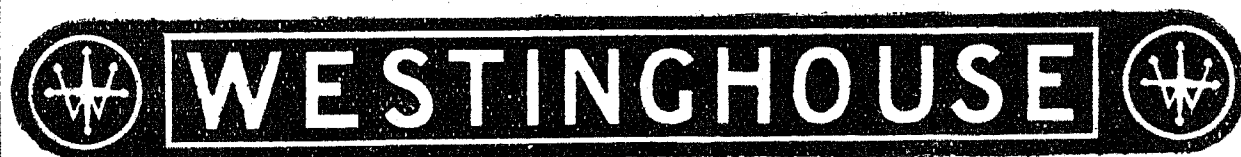
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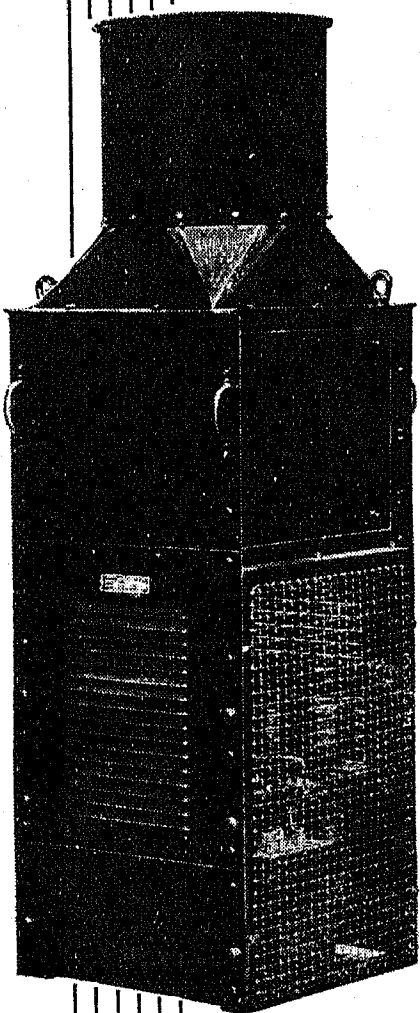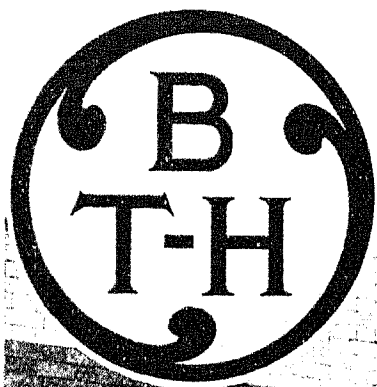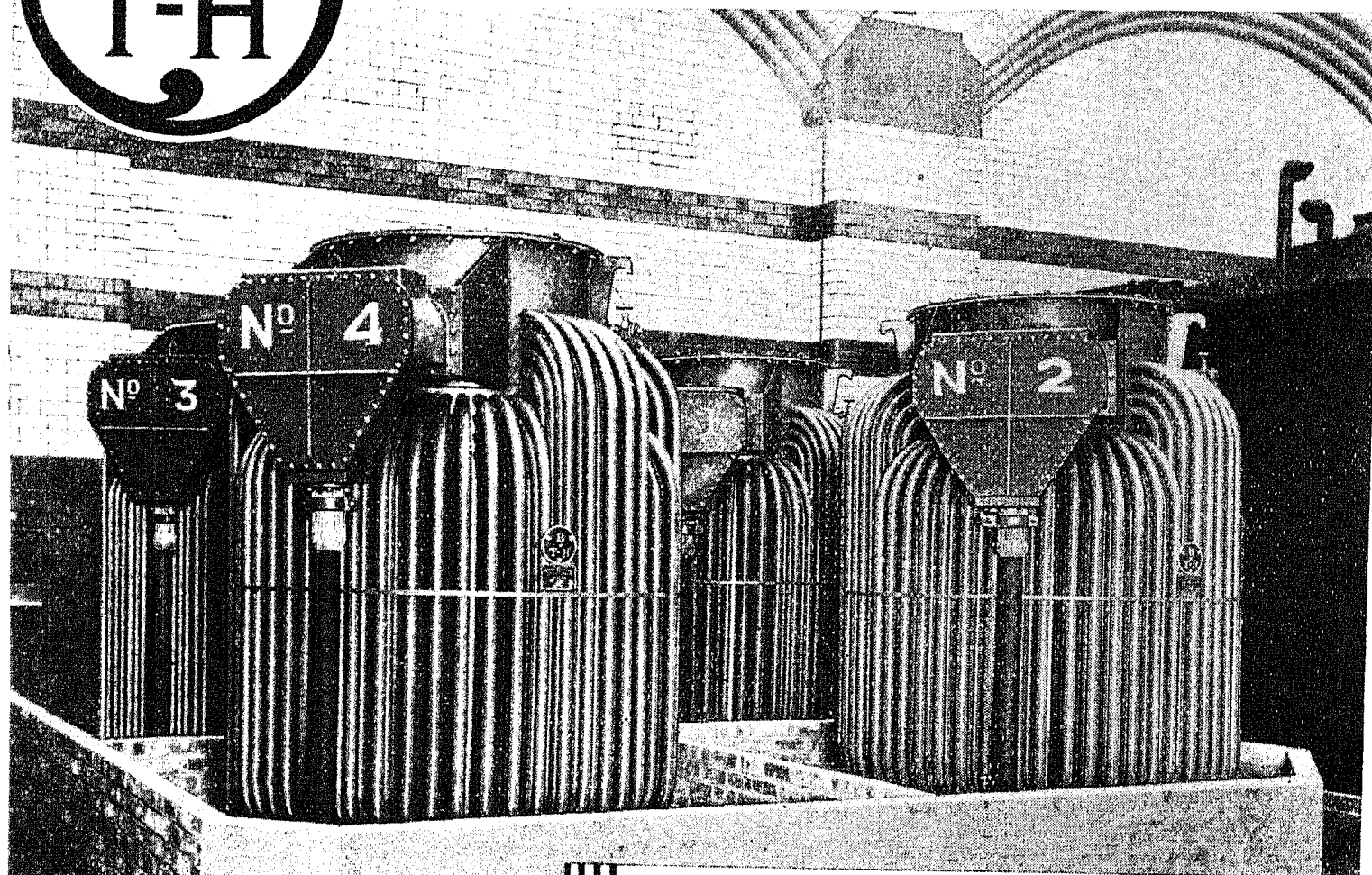
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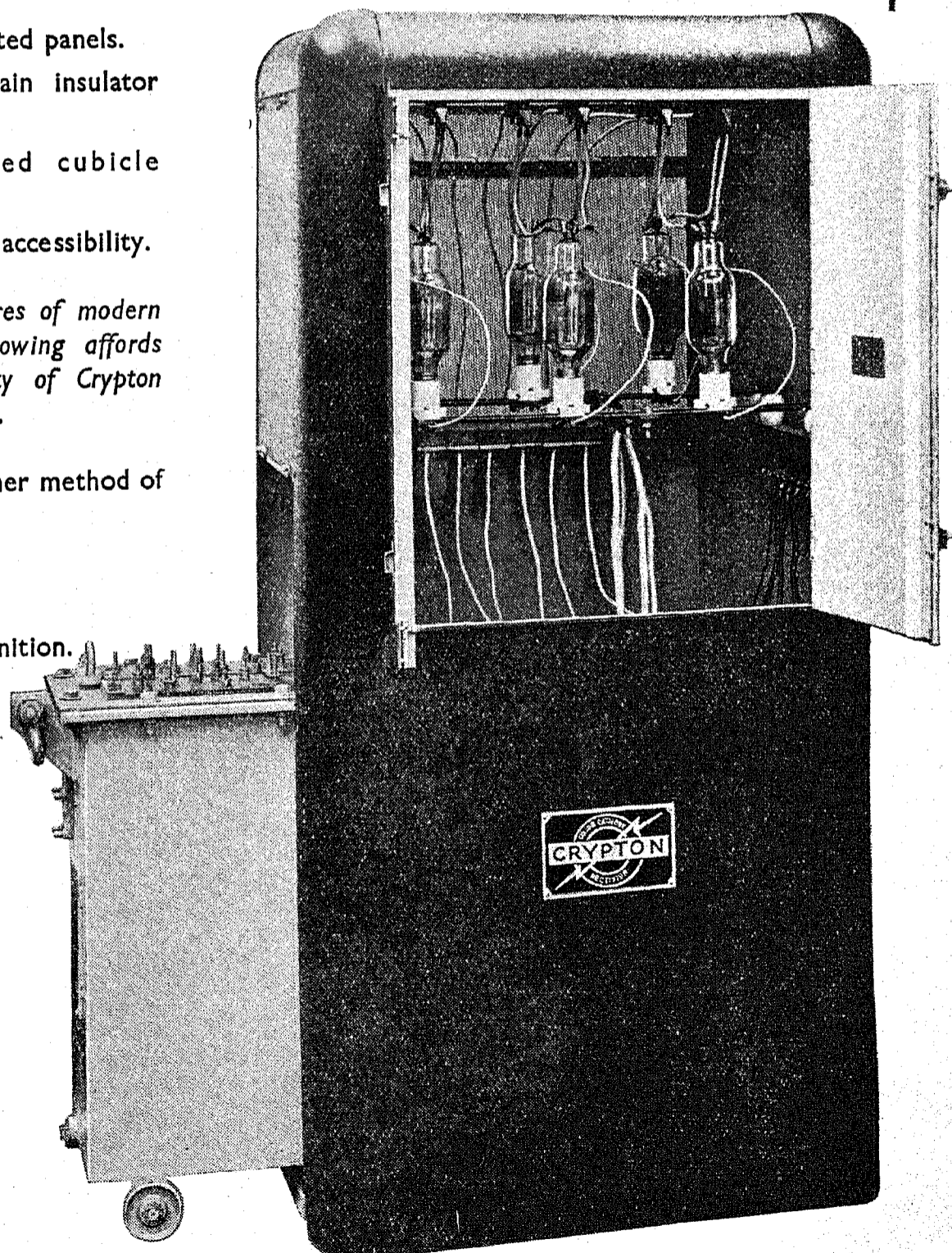
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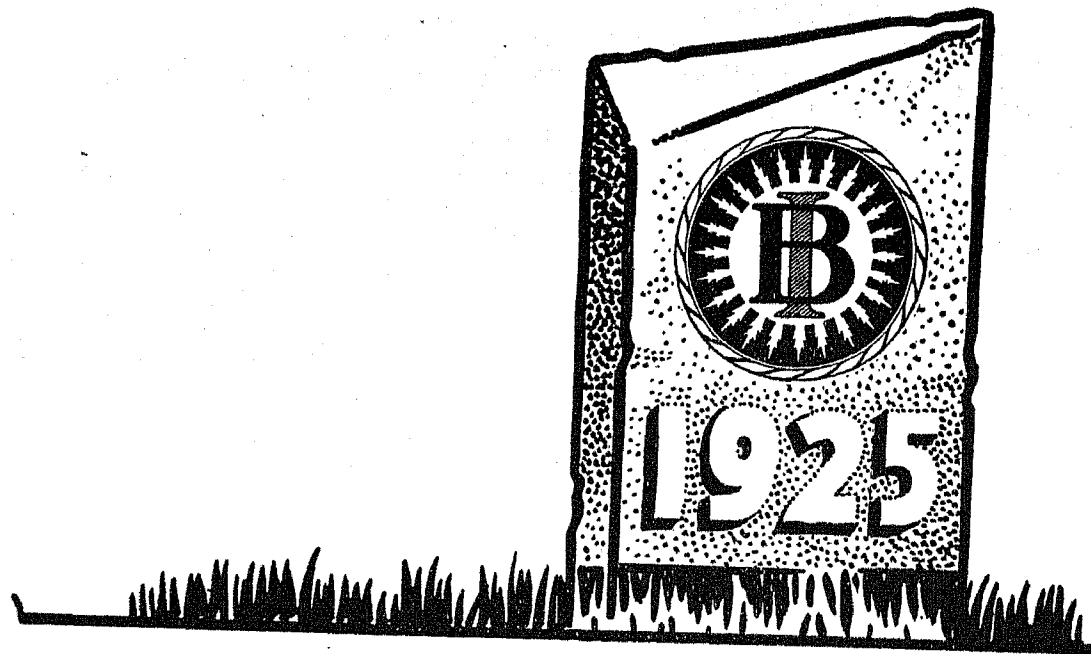
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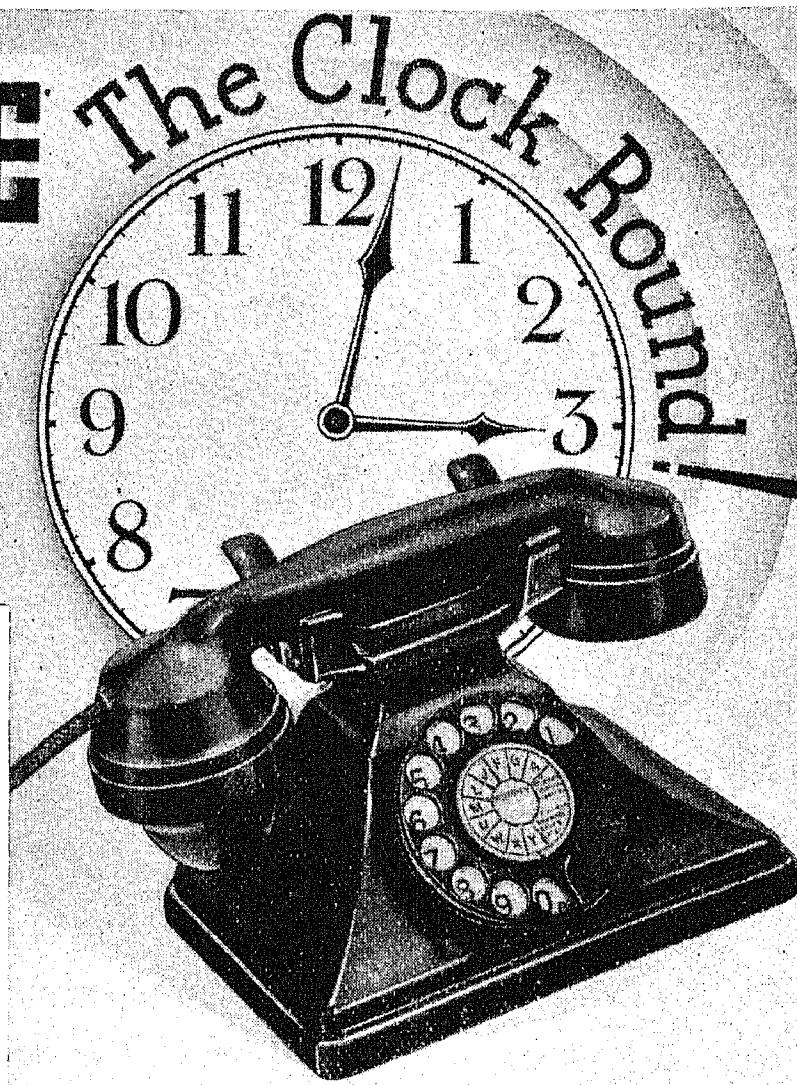
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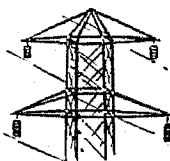
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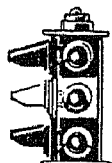
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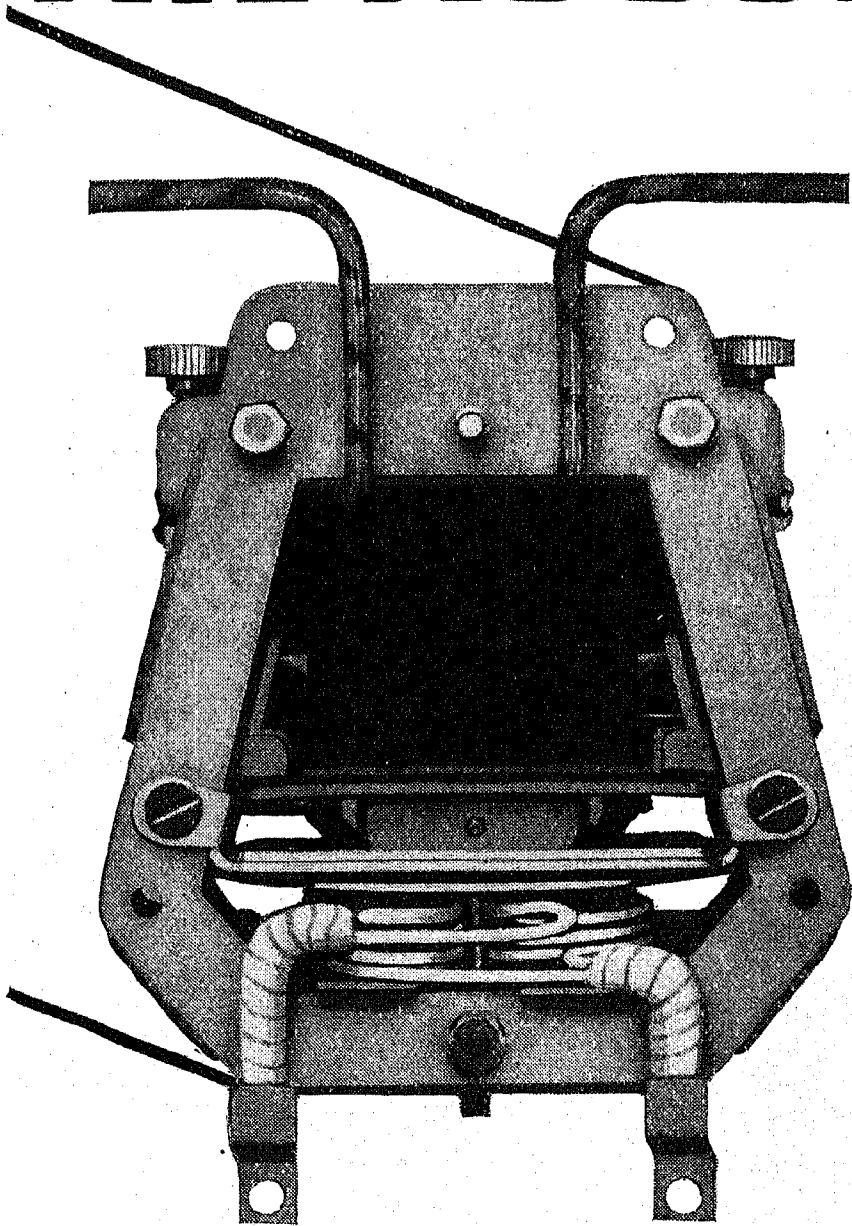
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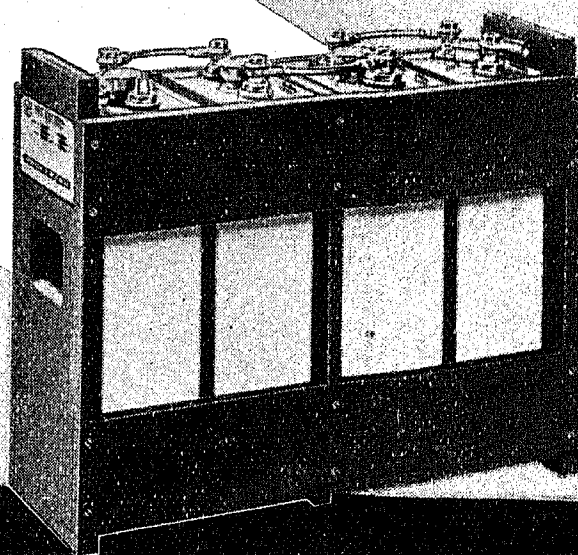
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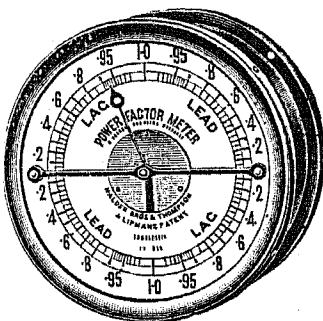*Form D.* For the Sale of Cables (Home, without erection). Issued April 1924. 6d.

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